High-Energy Nuclear Collisions and QCD Phase Structure

- Recent Results from STAR Experiment at RHIC

Nu Xu

(1)*Nuclear Science Division, LBNL, USA*

(2)*School of Physical Science & Technology, CCNU, China*

Outline

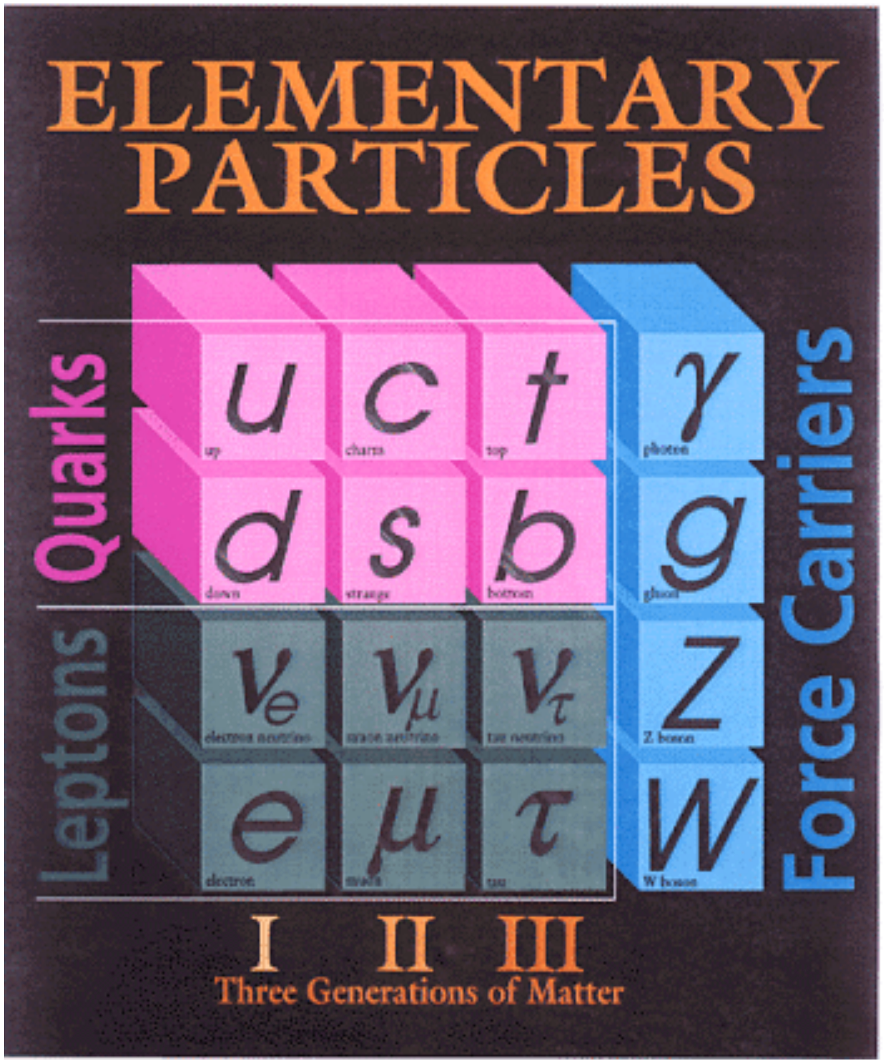
(1) Introduction

(2) STAR Experiment and Physics Program

(3) Recent Results from STAR at RHIC

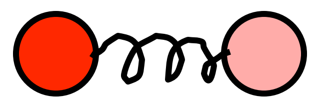
(4) STAR Upgrade Programs

Quantum Chromodynamics

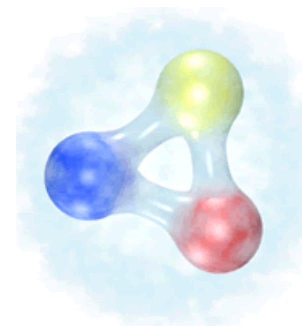


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson

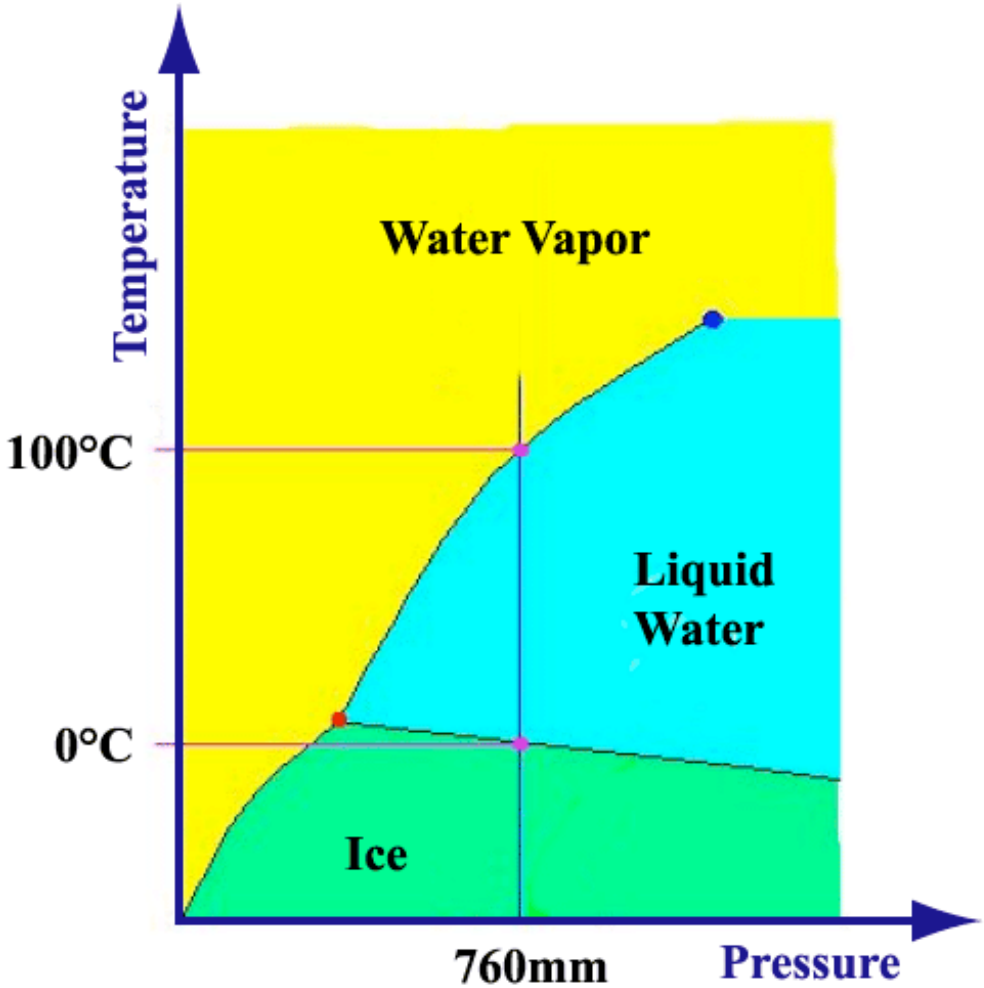


baryon



3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

Phase Diagram: Water



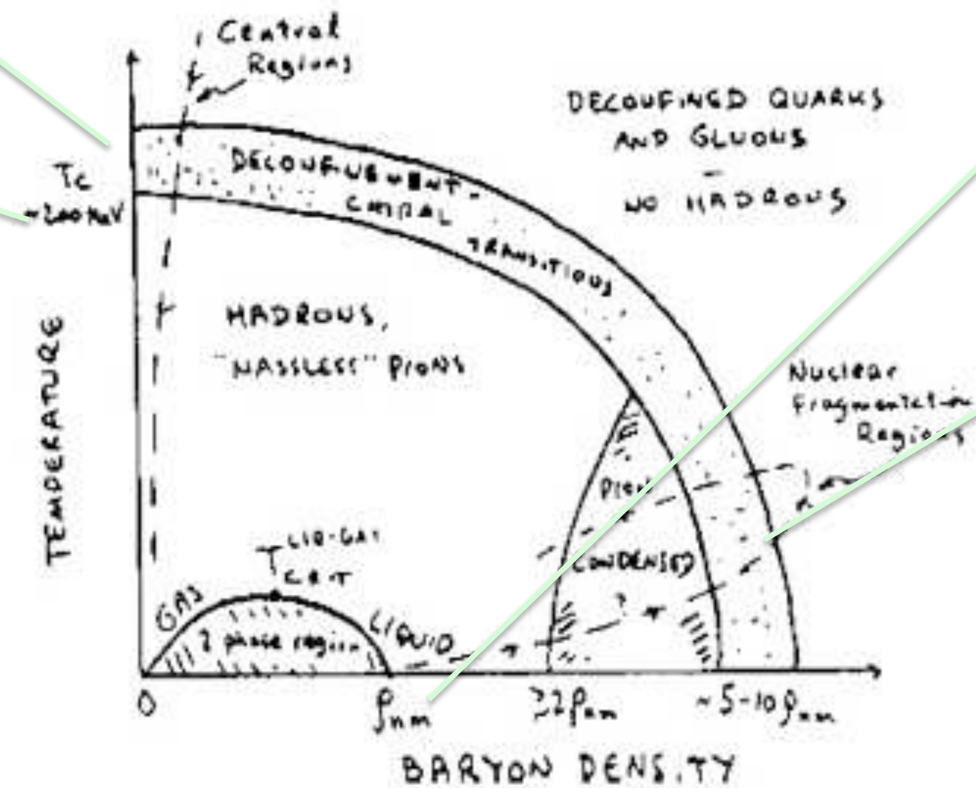
Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

QCD Phase Diagram 1983

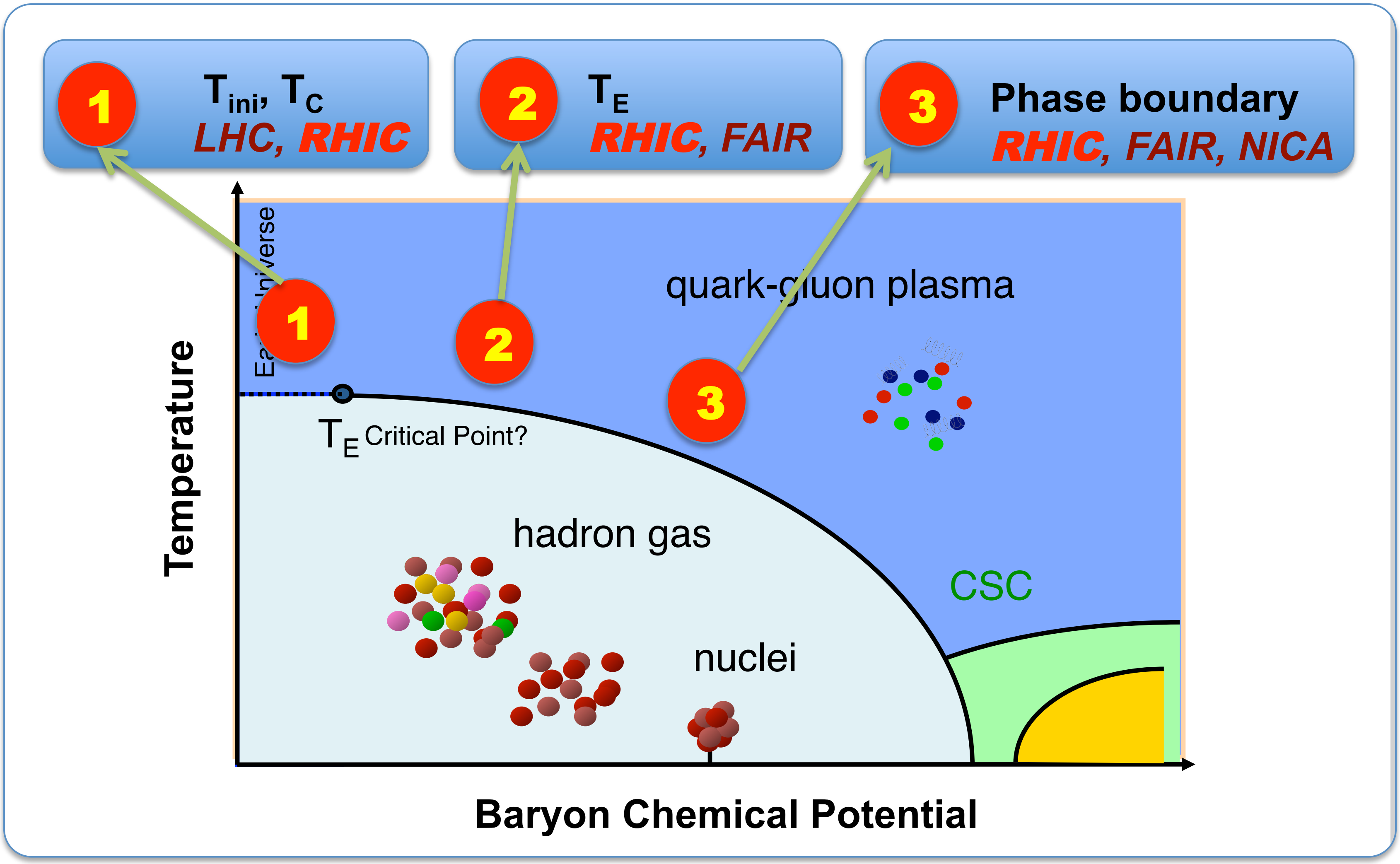
1983 US Long Range Plan *- by Gordon Baym*

T_C~200 MeV

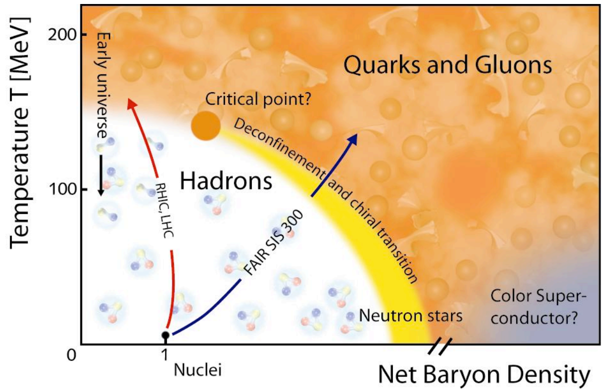
(1, 2, 5-10)*ρ_0



The QCD Phase Diagram and High-Energy Nuclear Collisions

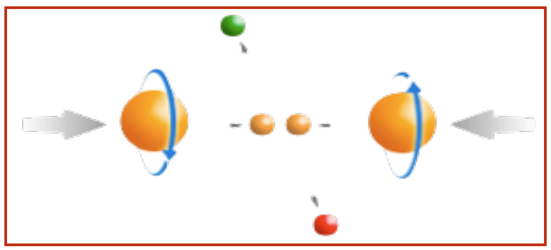


STAR Physics Focus

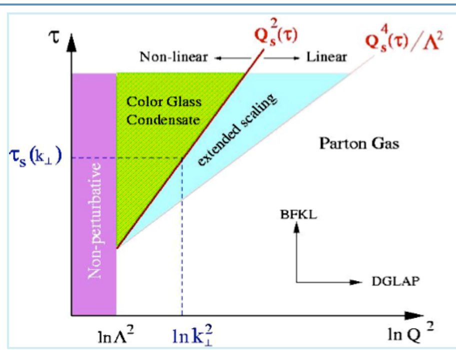


1) At 200 GeV top energy
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration



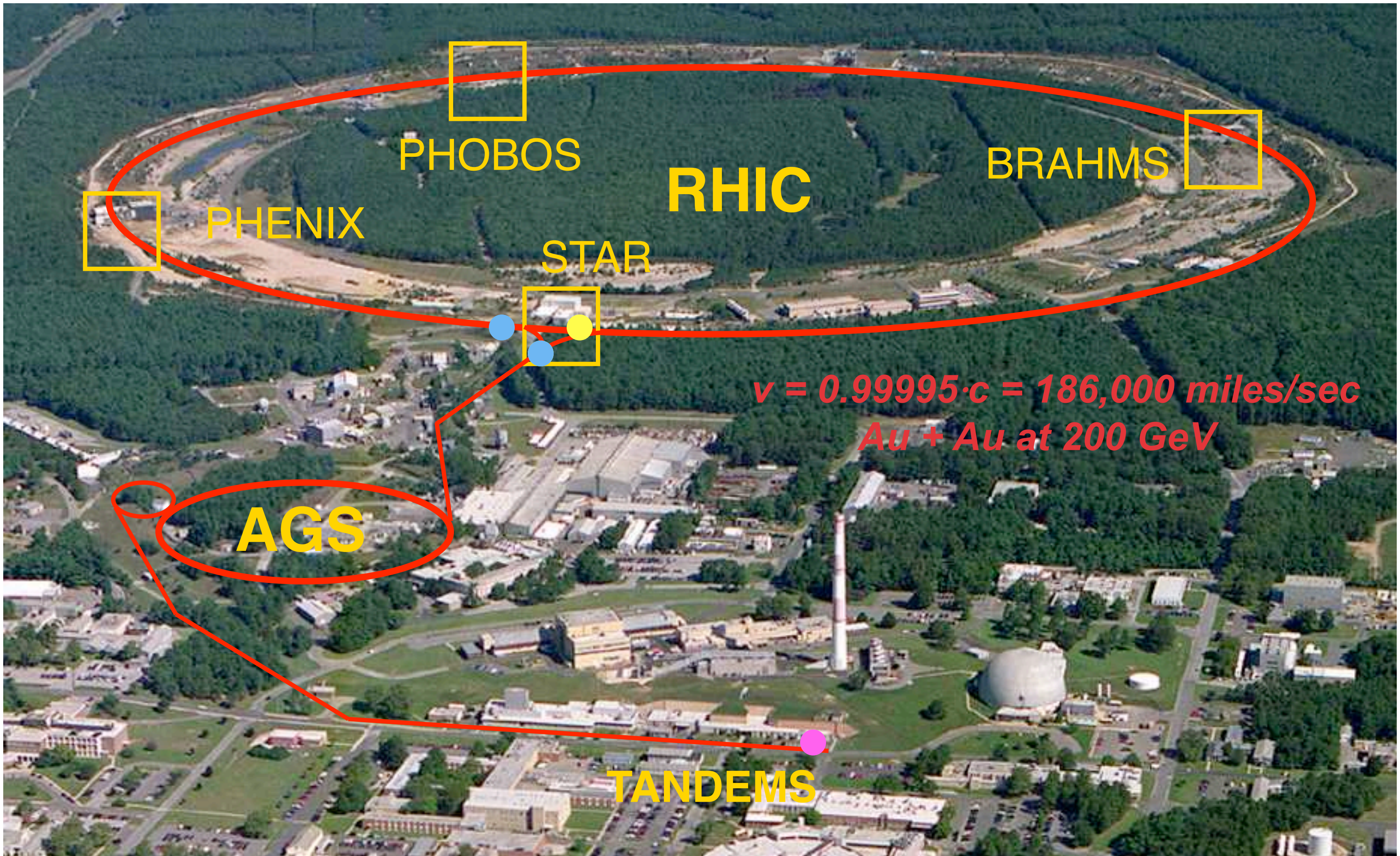
Polarized *p+p* program
- Study ***proton intrinsic properties***



Forward program
- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***

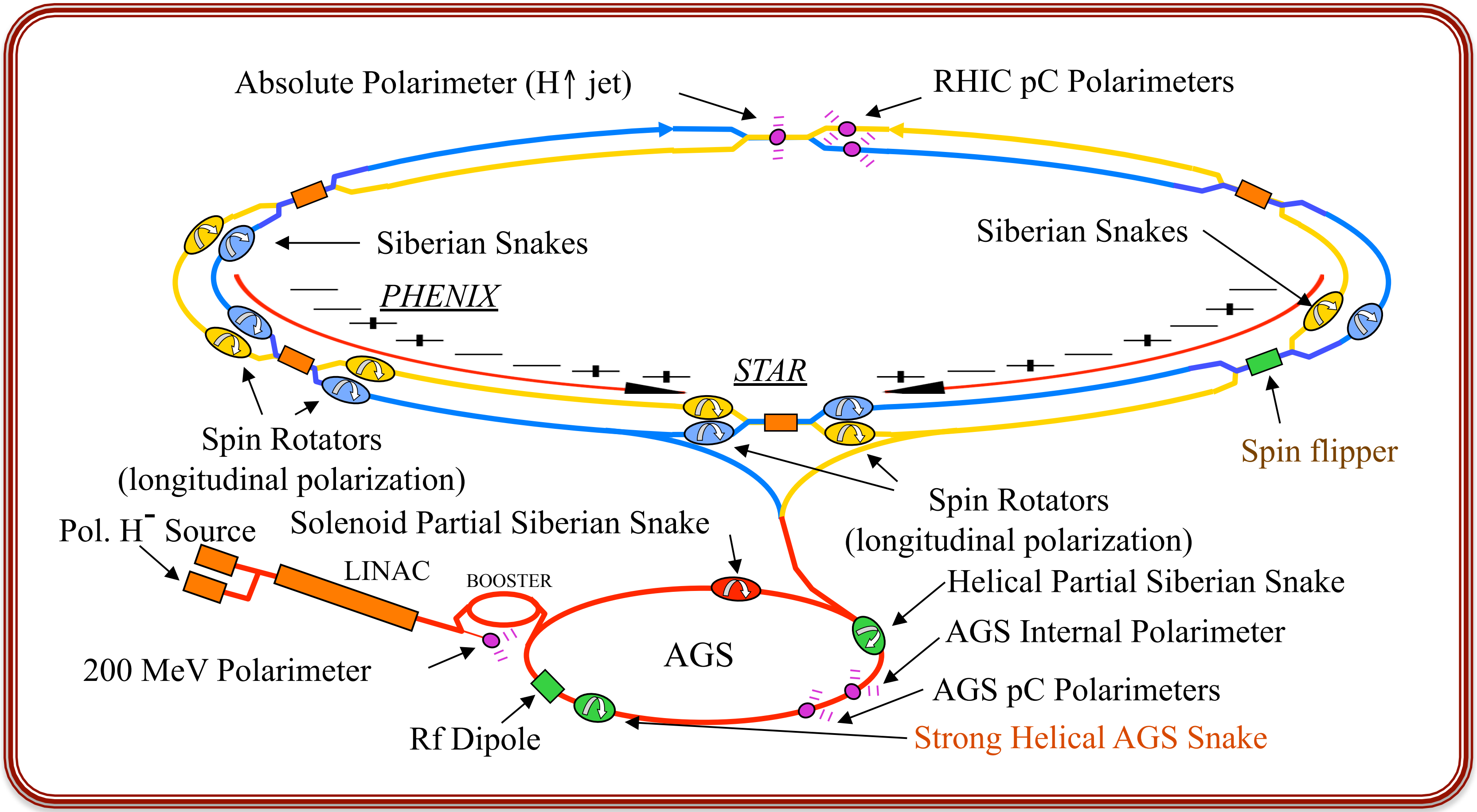
Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



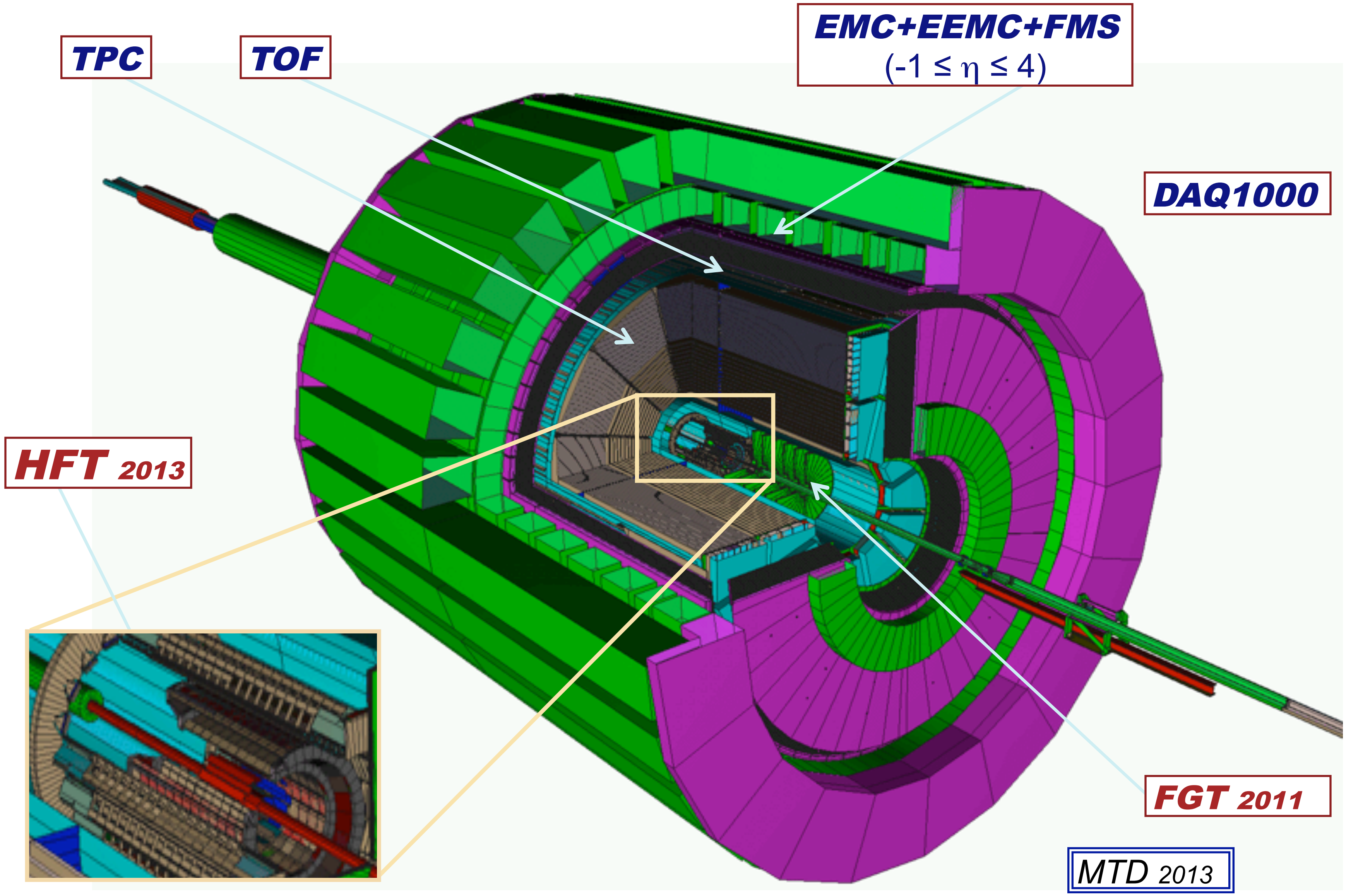
Animation M. Lisa

RHIC: Polarized Hadron Collider

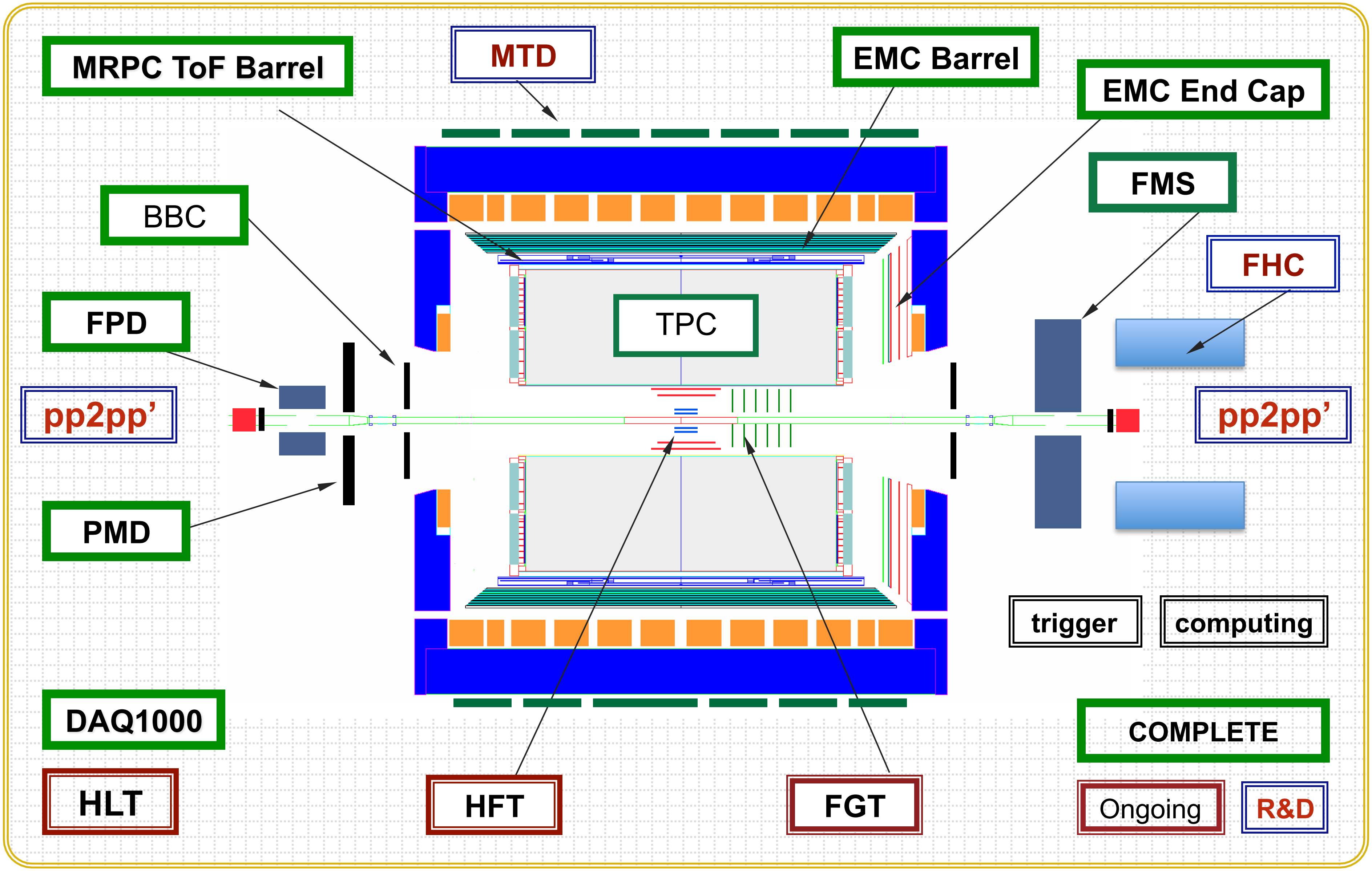


- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- "Billions" of spin reversals during a fill

STAR Detectors *Fast* and *Full azimuthal particle identification*

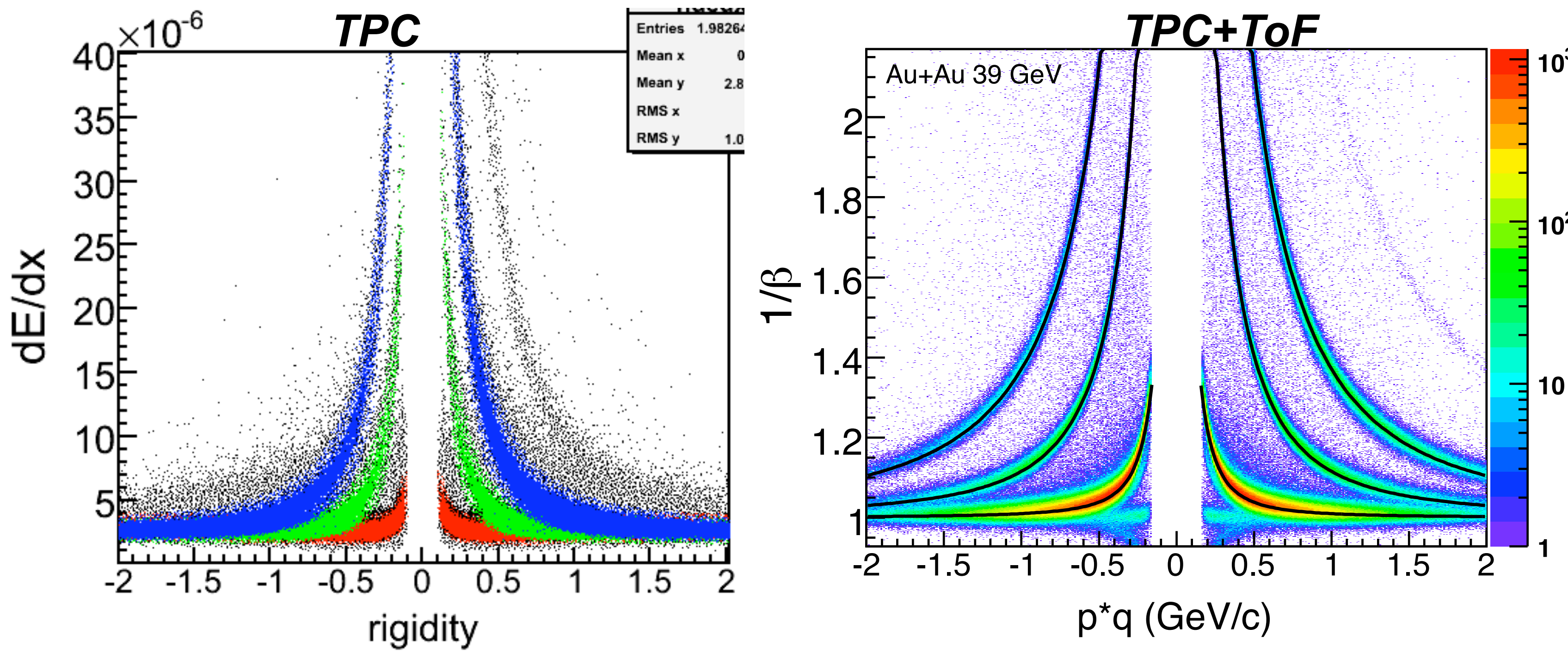


STAR Experiment



Run 10 Performance

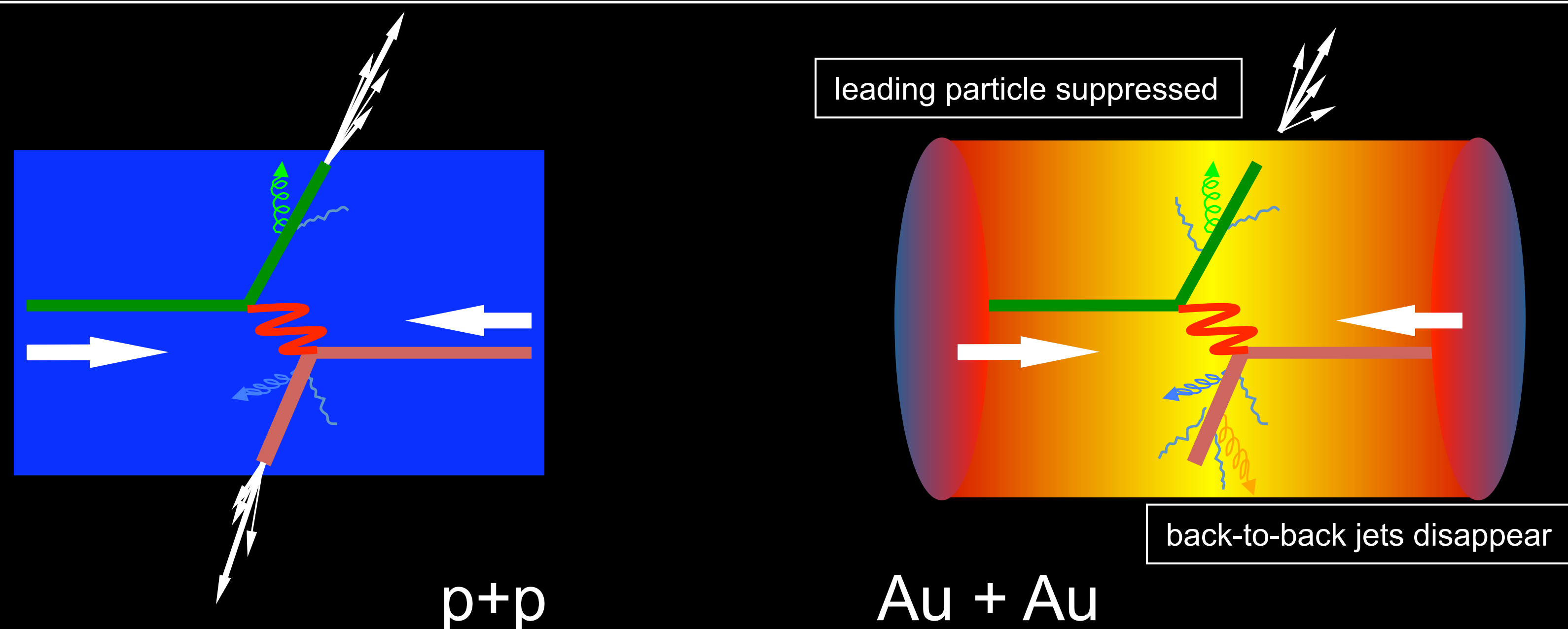
$\sqrt{s_{NN}}$ = 39 GeV Au + Au Collisions

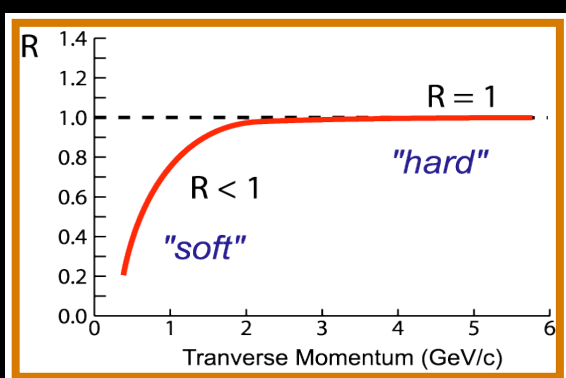


Beam Energy	Timing Resolution	Remarks
200 (GeV)	85 (*ps*)	At 39 GeV, using a new calibration scheme without information of start time from VPD, 87 *ps* of timing resolution has been achieved.
62.4 (GeV)	90 (*ps*)	
39 (GeV)	85 (*ps*)	
11.5 & 7.7 (GeV)	~ 80 (*ps*)	

Selected STAR Heavy Ion Results

Energy Loss in A+A Collisions

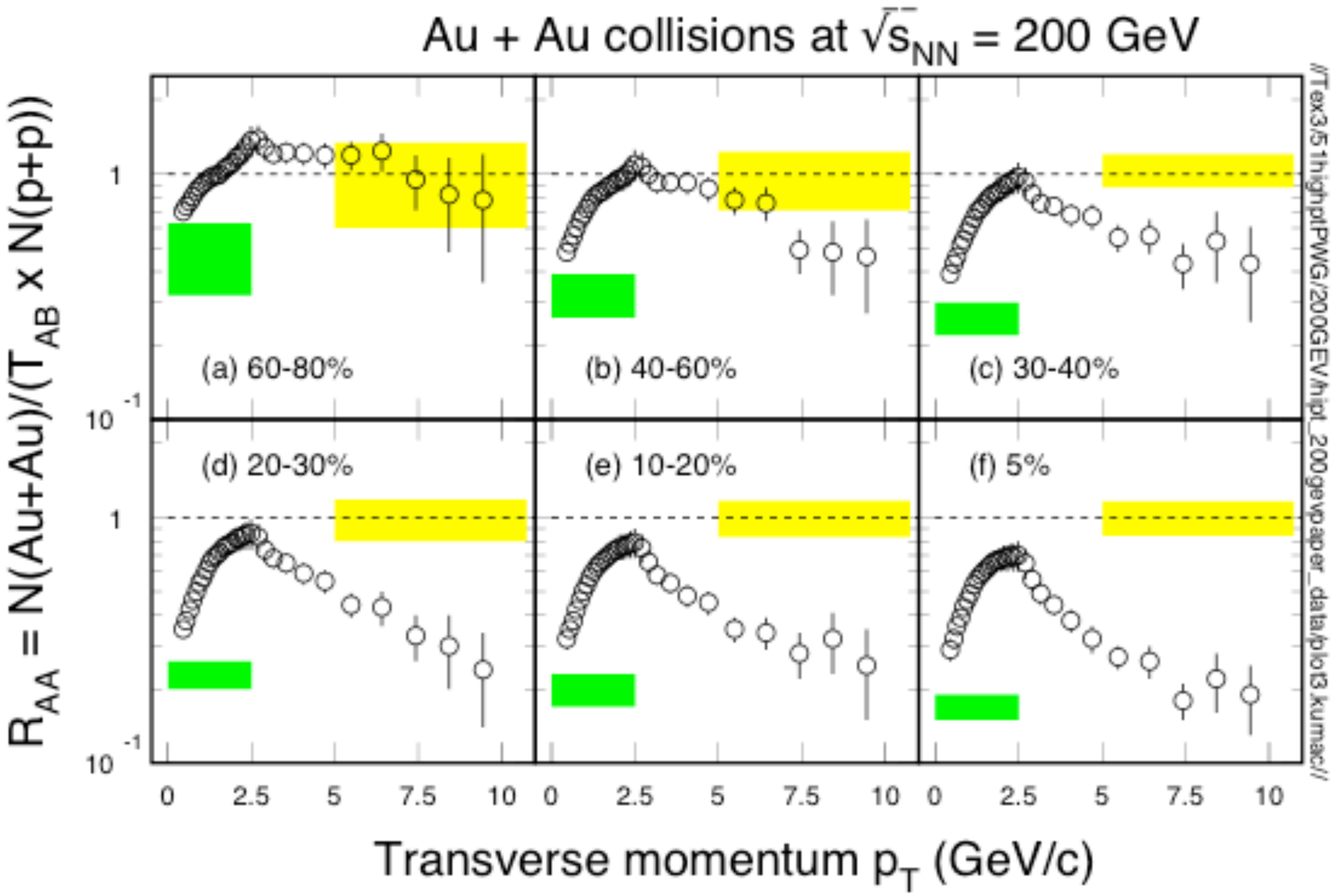




Nuclear Modification Factor:

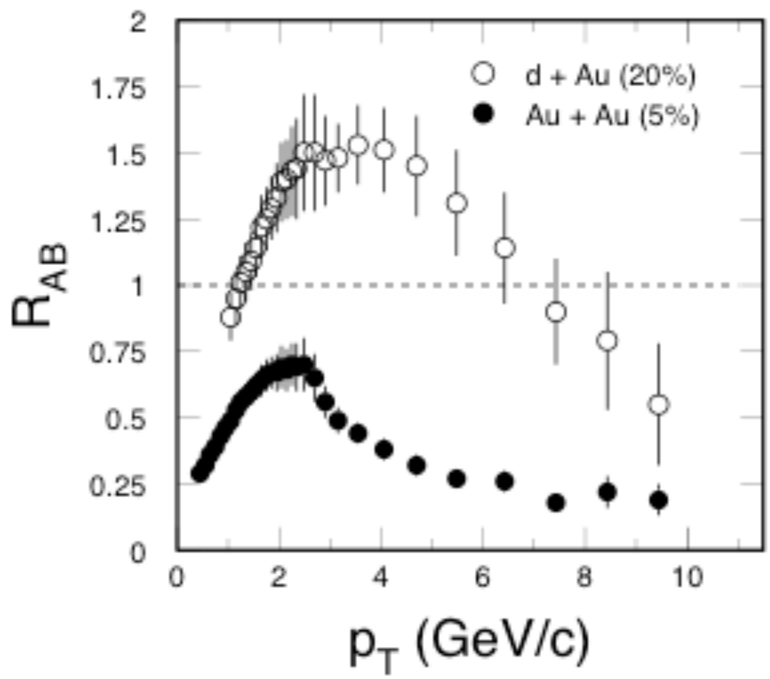
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

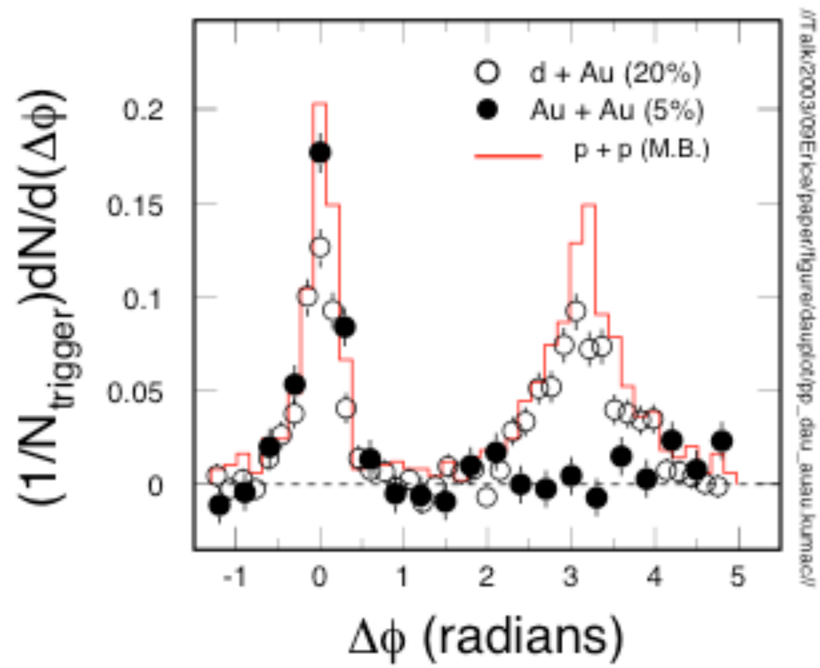
Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

Suppression and Correlations





In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

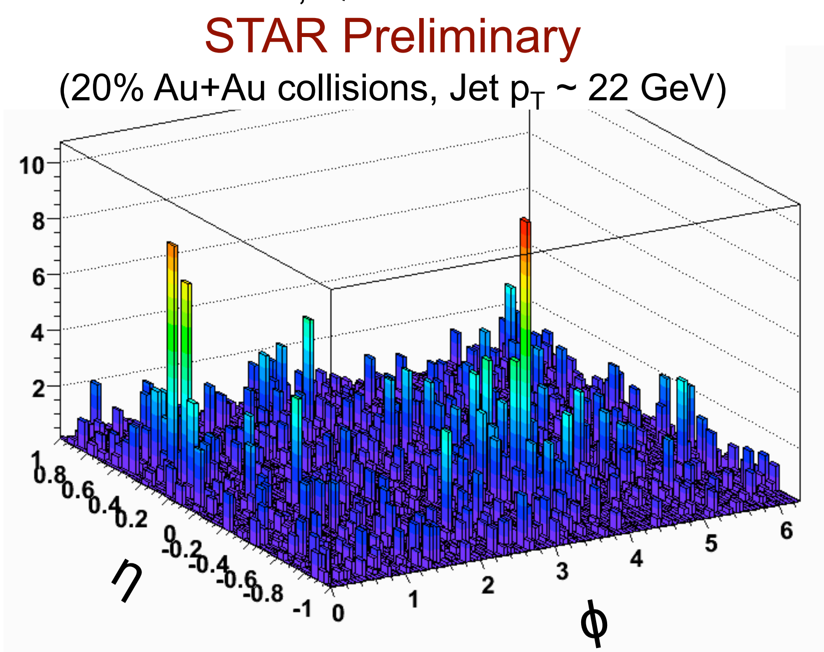
Parton energy loss: Bjorken 1982

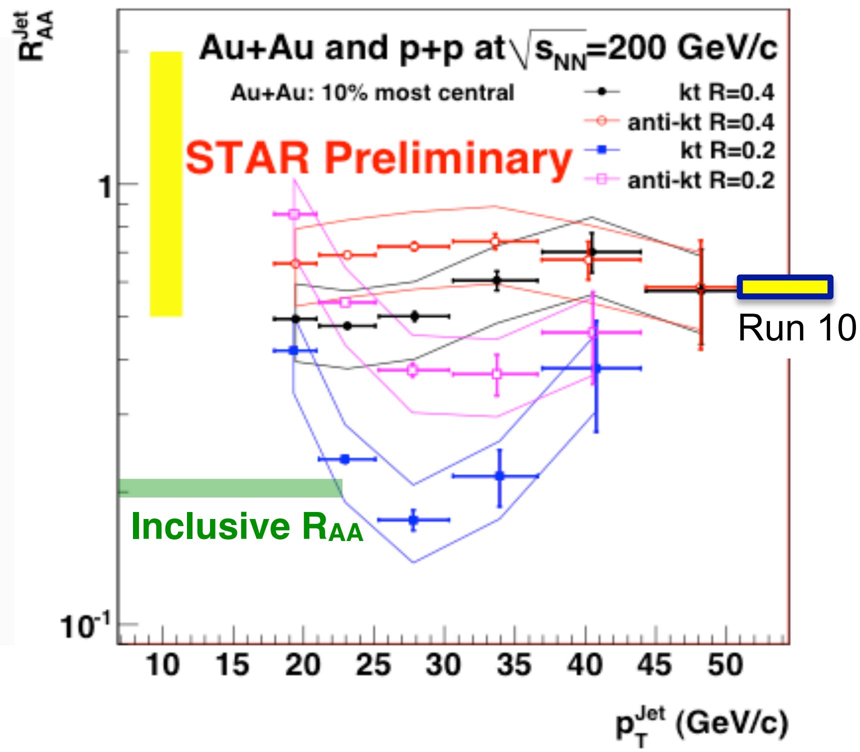
("**Jet quenching**") Gyulassy & Wang 1992

…

Full Jet Recon in AA Collisions

Joern Putschke, QM2009





1) Jets are seen in Au+Au collisions, extended the kinematical reach to jet energies > 40 GeV in central Au+Au collisions at RHIC

2) We see a substantial fraction of jets - in contrast to x5 suppression for light hadron R_{AA}

Pressure Gradient, Collectivity, Flow

$$\tau d\sigma = dU + pdV$$

σ– entropy; p – pressure; U – internal energy; V – volume
$\tau = k_B T$, thermal energy per dof

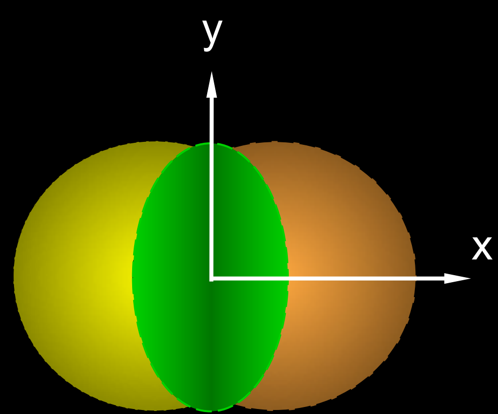
In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

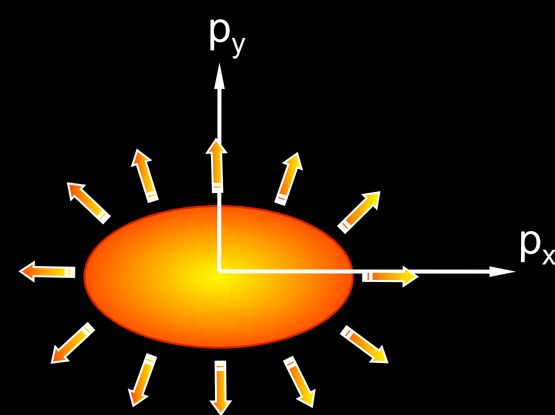
pressure gradient $\Leftrightarrow$ ***collective flow***

$\Leftrightarrow$ number of degrees of freedom (dof)
$\Leftrightarrow$ Equation of State (EOS)
$\Leftrightarrow$ No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.
$\Rightarrow$ Space-time-momentum correlations!

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

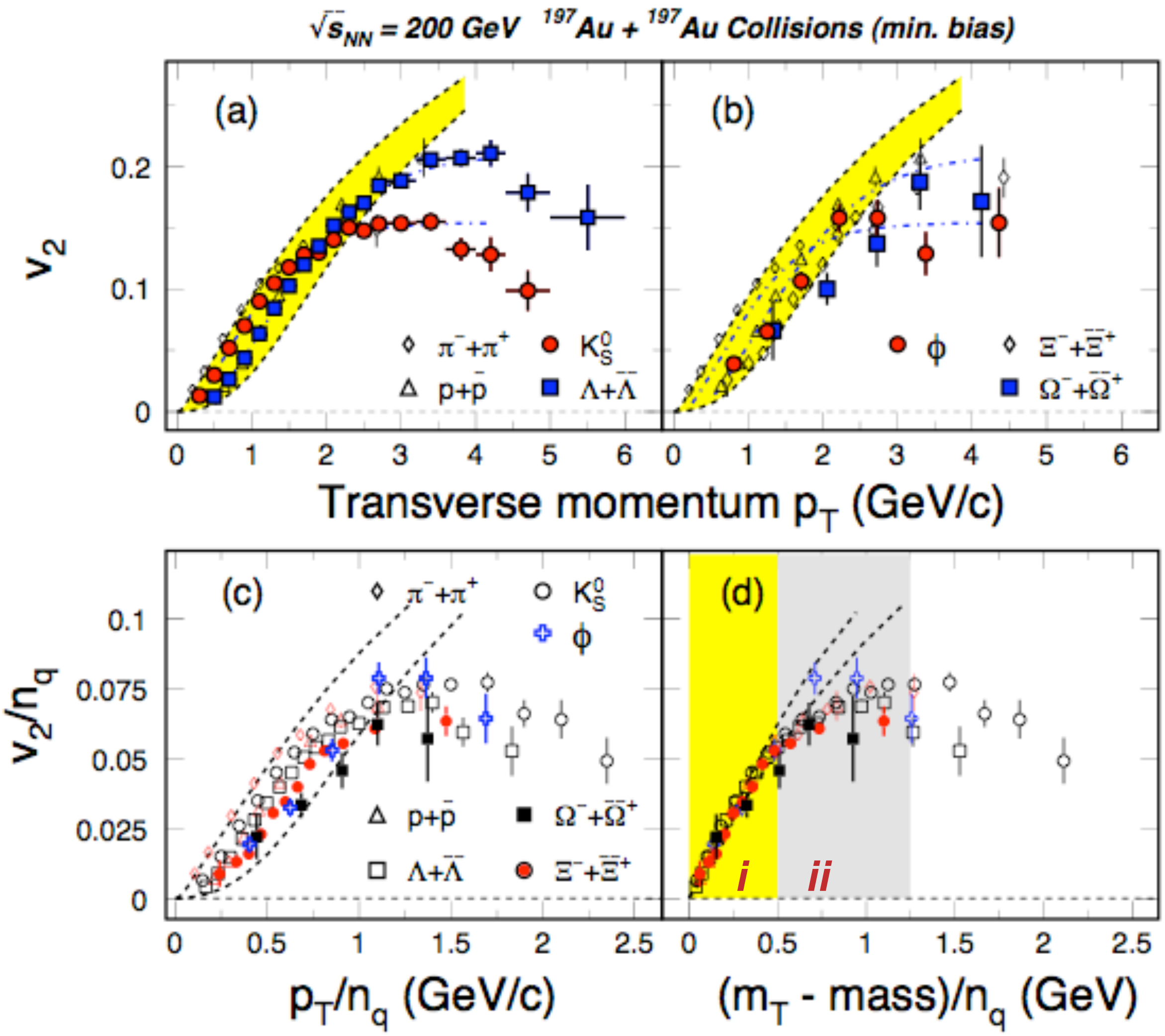




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, De-confinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

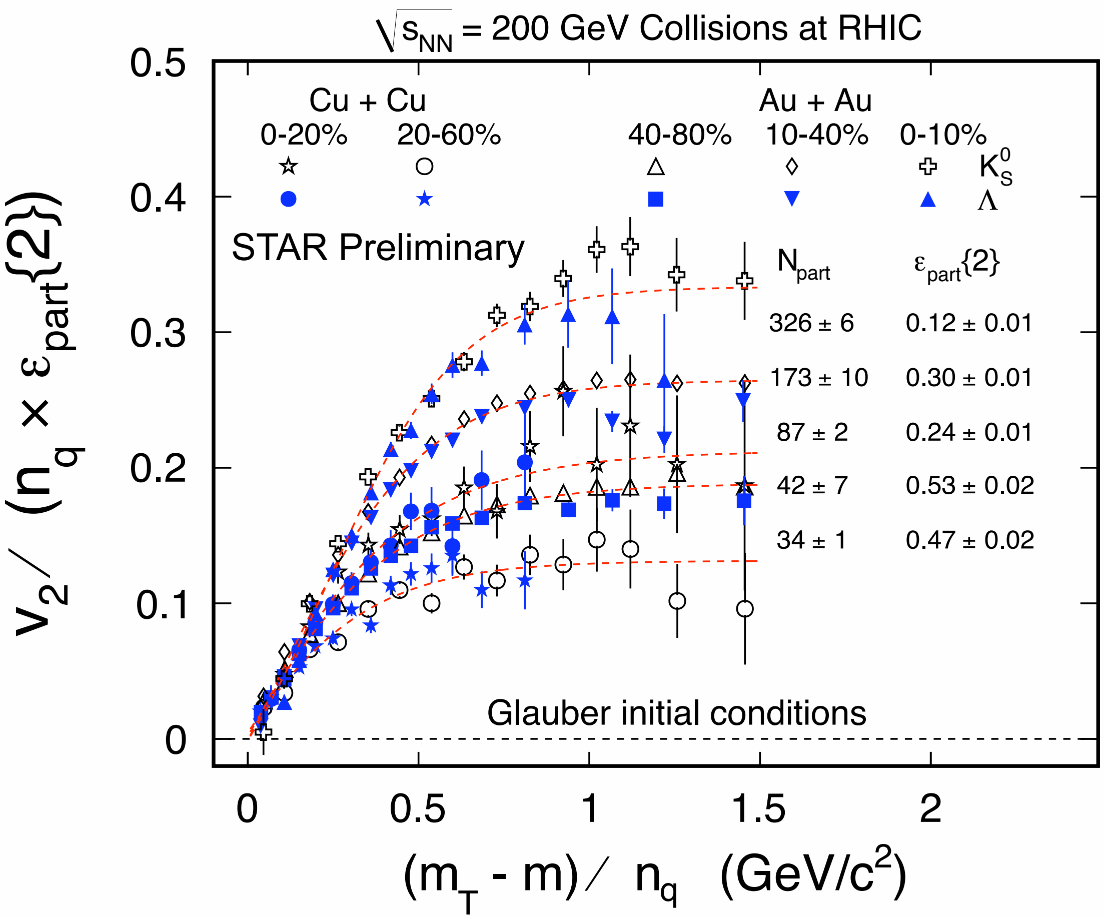
➪ **n_q-scaling**
novel hadronization process

➪ **Partonic flow**
De-confinement

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

System Size Driven Collectivity



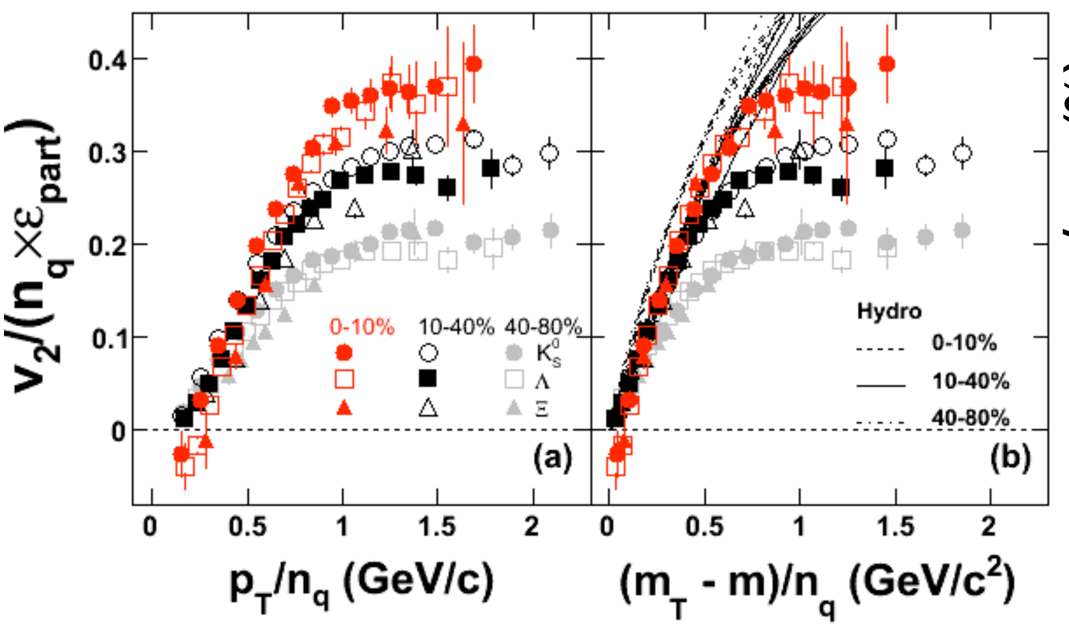
Collectivity: Driven by number of participants and eccentricity.

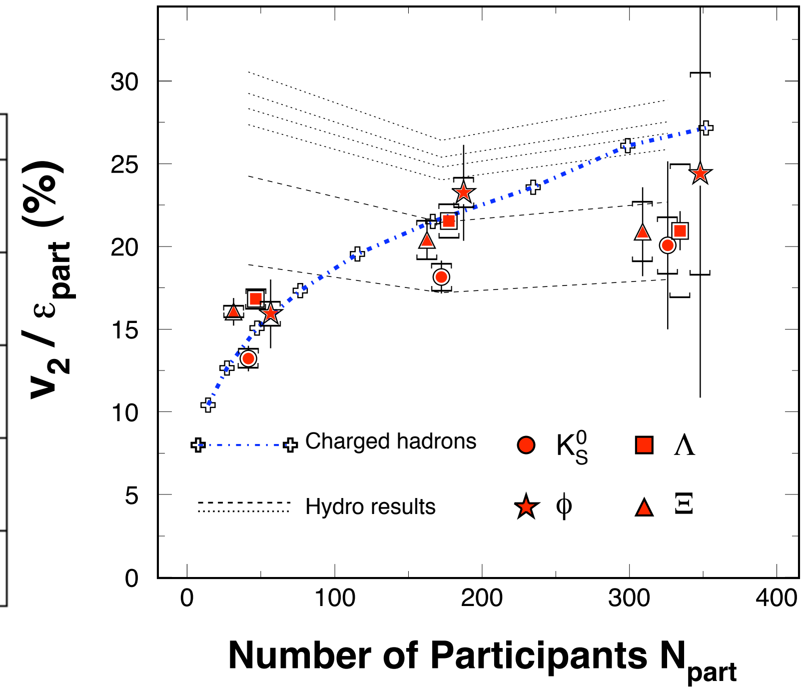
Caution: Local equilibrium and perfect fluid

200 GeV: v_2 Centrality Dependence

STAR: Phys. Rev. ***C77****, 54901(2008)*

200 GeV Au+Au

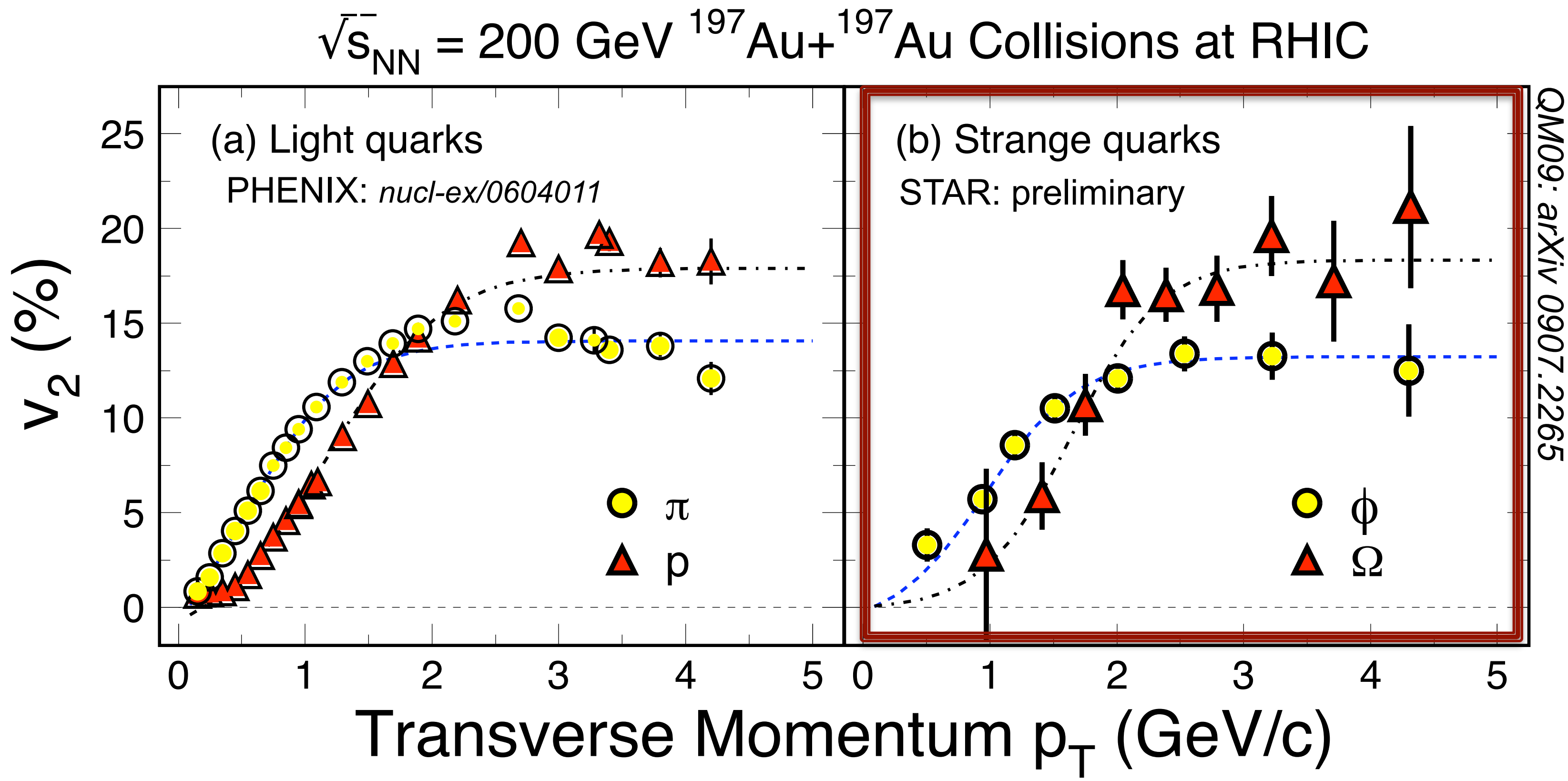




S. Voloshin, A. Poskanzer, PL ***B474****, 27(00).*
D. Teaney, et. al., nucl-th/0110037

- Larger v_2/ε_{part} indicates stronger flow in more central collisions.
- ***NO*** ε_{part} scaling.
- The observed n_q-scaling does not necessarily mean thermalization, viscosities?!

Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): number of quarks ordering
s-quark hadron: smaller interaction strength in hadronic medium
light- and s-quark hadrons: similar v_2 pattern

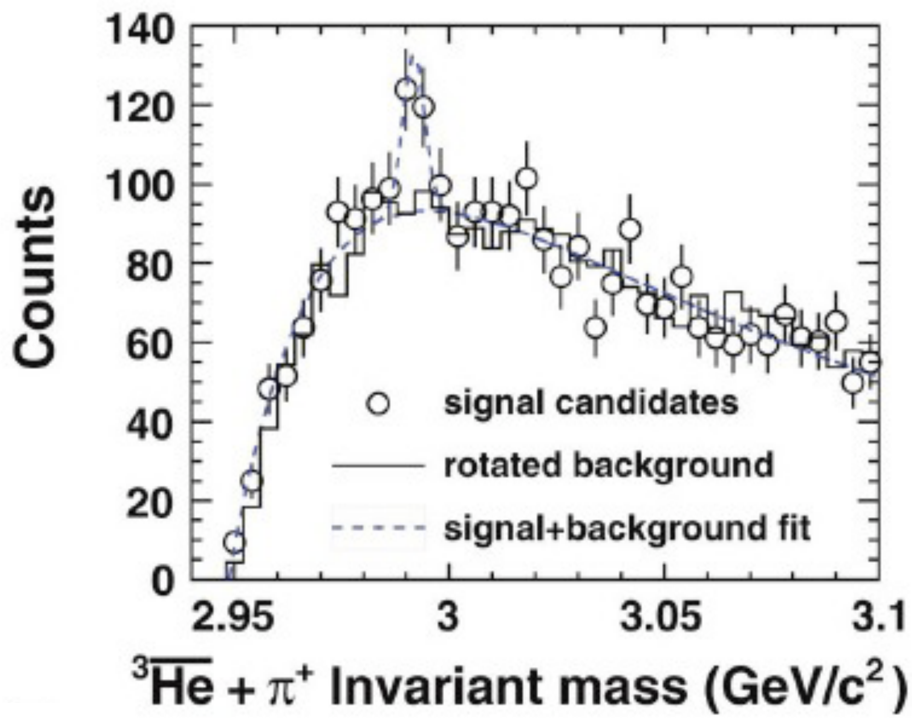
=> *Partonic Collectivity at RHIC !*

First Observation of ${}^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$

Sciencexpress **Research Article**

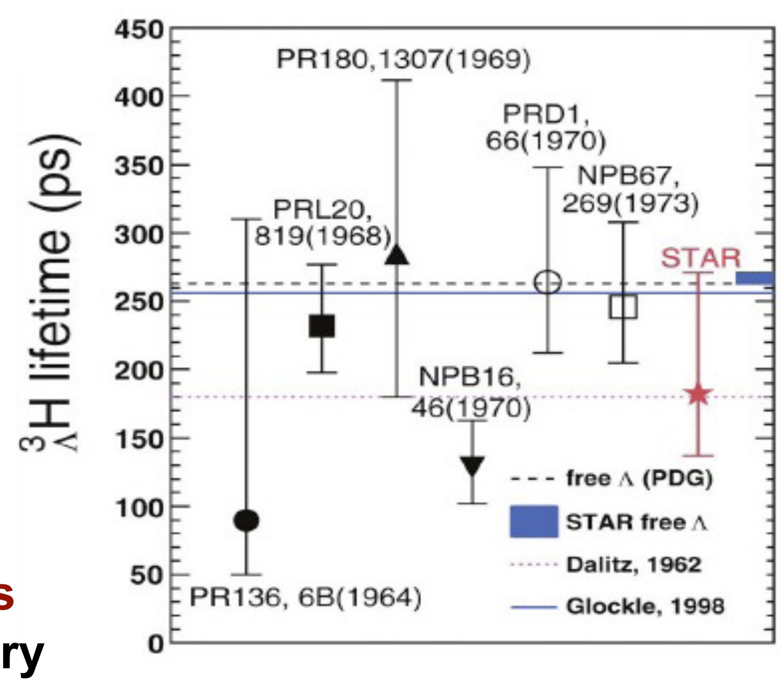
Observation of an Antimatter Hypernucleus

The STAR Collaboration*†



200 GeV Au+Au collisions at RHIC

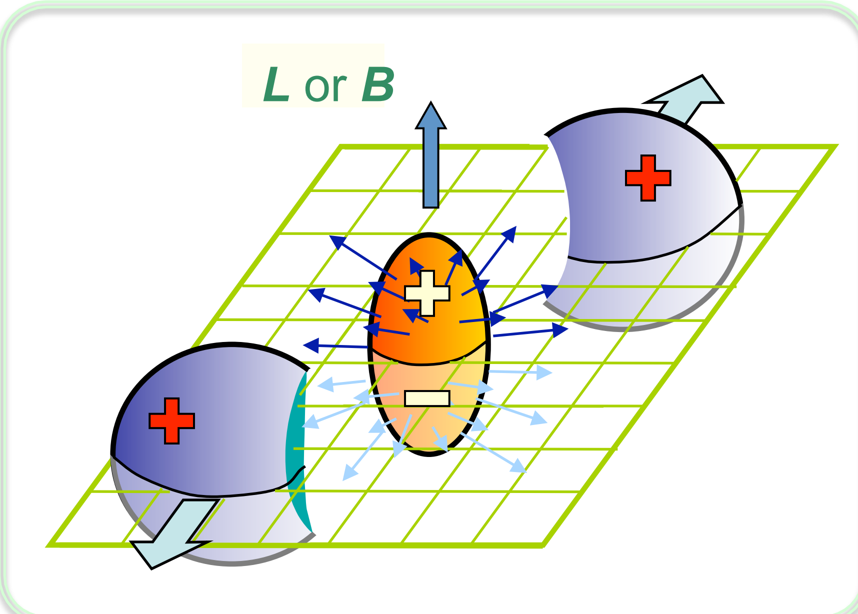
- Equilibrium of s-quarks
- Thermal models (Stachel *et al*.)



- First observation of the anti-hypernucleus
- Heaviest anti-matter observed in laboratory

Search for Local Parity Violation

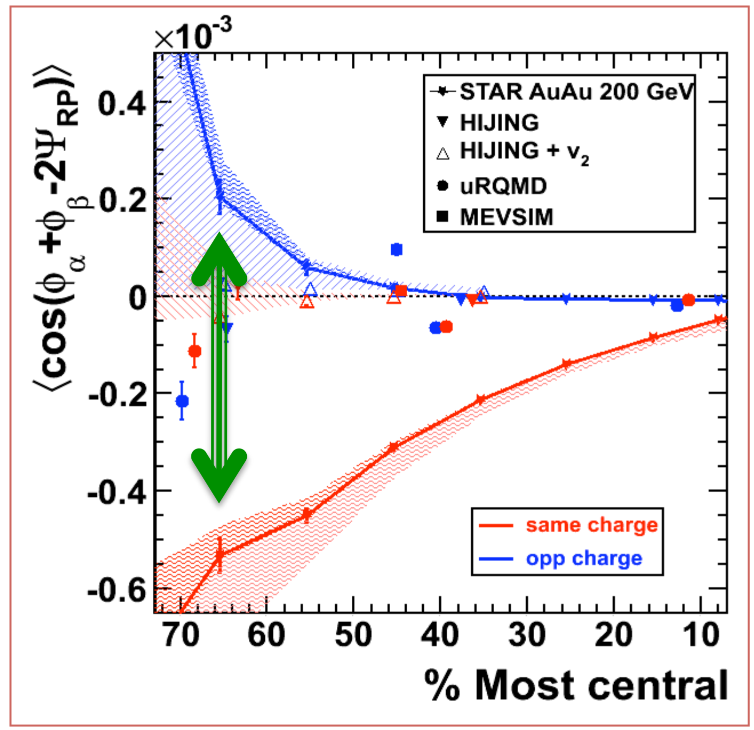
in High Energy Nuclear Collisions



$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

STAR; PRL **103**, 251601(09);
PRC **81**, 54908(10).



The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement*** **and** ***Chiral symmetry restoration***

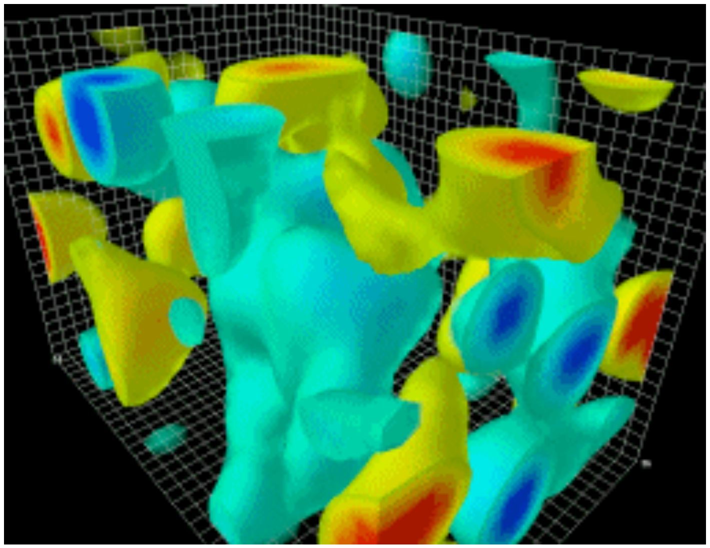
Run 11 requests:

Beam Energy Dependence & U+U

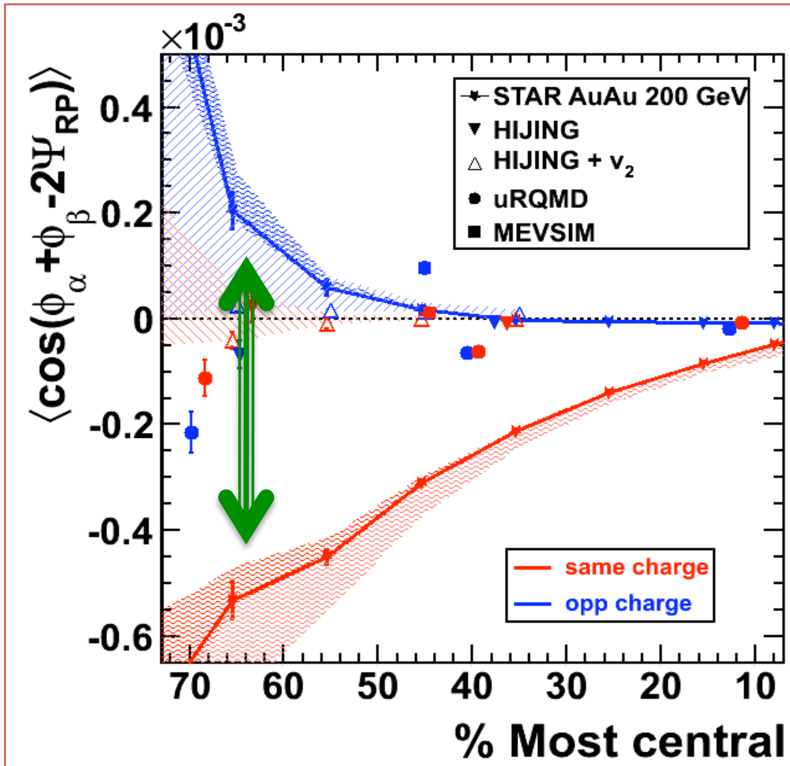
Search for Local Parity Violation

in High Energy Nuclear Collisions

Animation by *Derek Leinweber*



Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous strong* parity violation would be a clear proof for the existence of such physics.

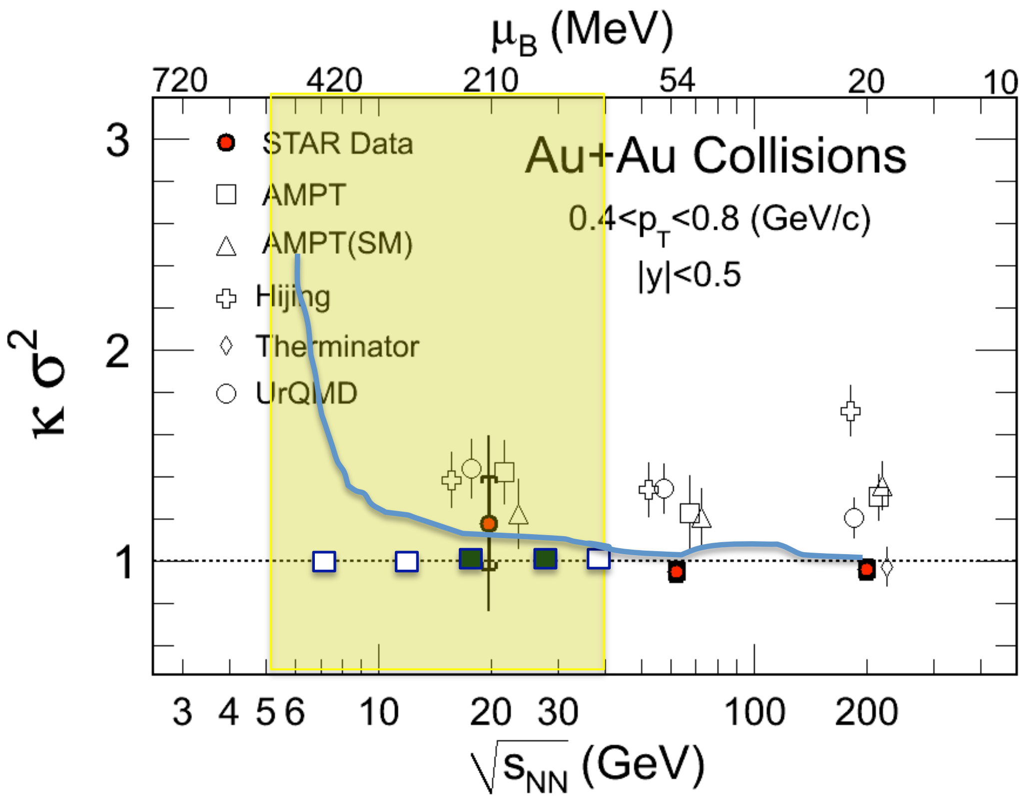


Chiral Magnetic Effect:

Kharzeev, PL B633 260 (2006).
Kharzeev, Zhitnitsky, NP A797 67(07).
Kharzeev, McLerran, Warringa, NP A803 227(08).
Fukushima, Kharzeev, Warringa, PR D78, 074033(08).

Net-proton High Moments

STAR: 1004.4959, PRL



Estimated errors in Au+Au collision :

□ Run 10: 7.7, 11.5, 39 GeV

■ **Run 11: 18, 27 GeV**

1) STAR results* on net-proton high moments for Au+Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4 and 19.6 GeV.

2) Sensitive to critical point**:

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

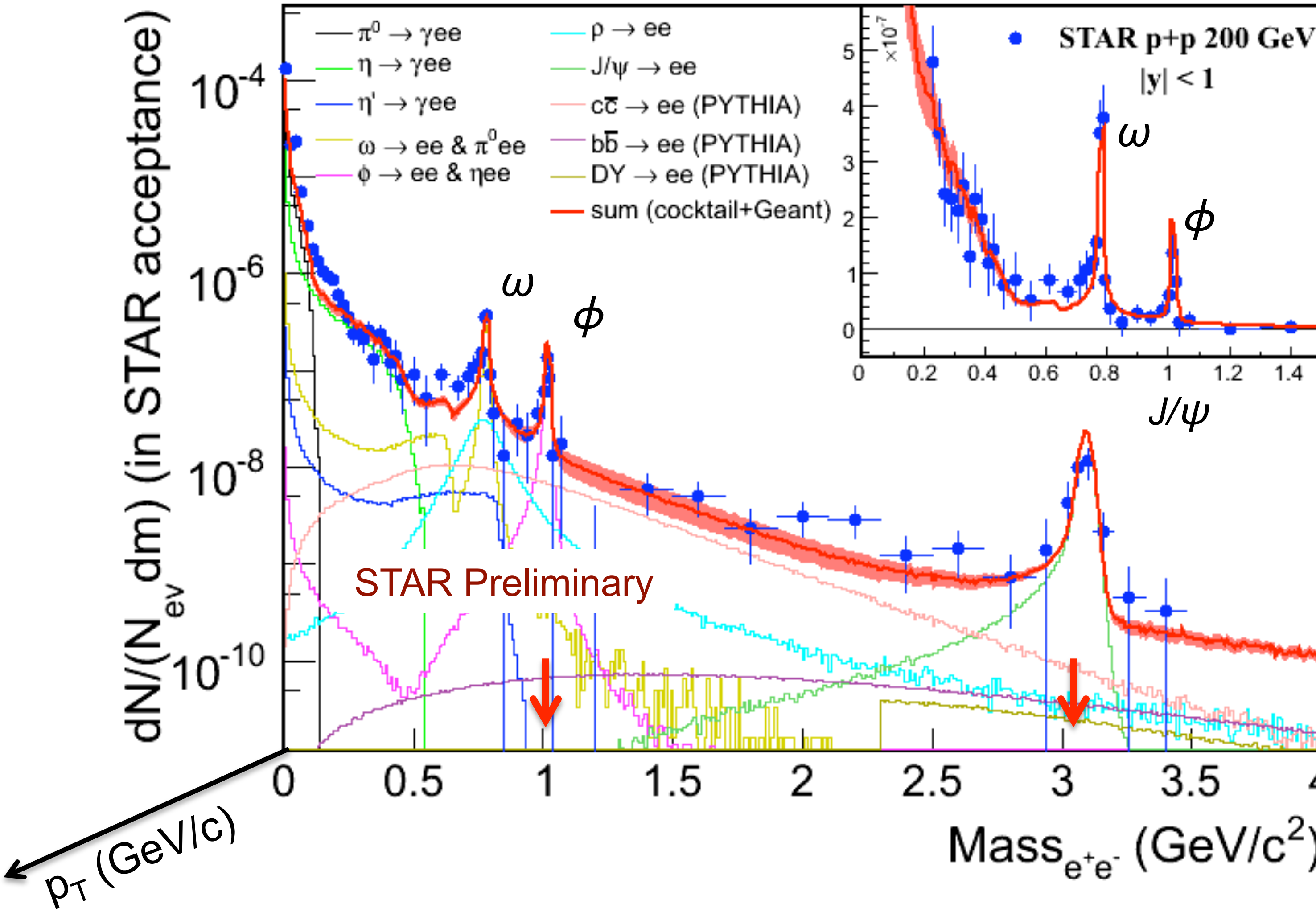
3) Direct comparison with Lattice results**:

$$S*\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa*\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent test on thermal equilibrium in heavy ion collisions.

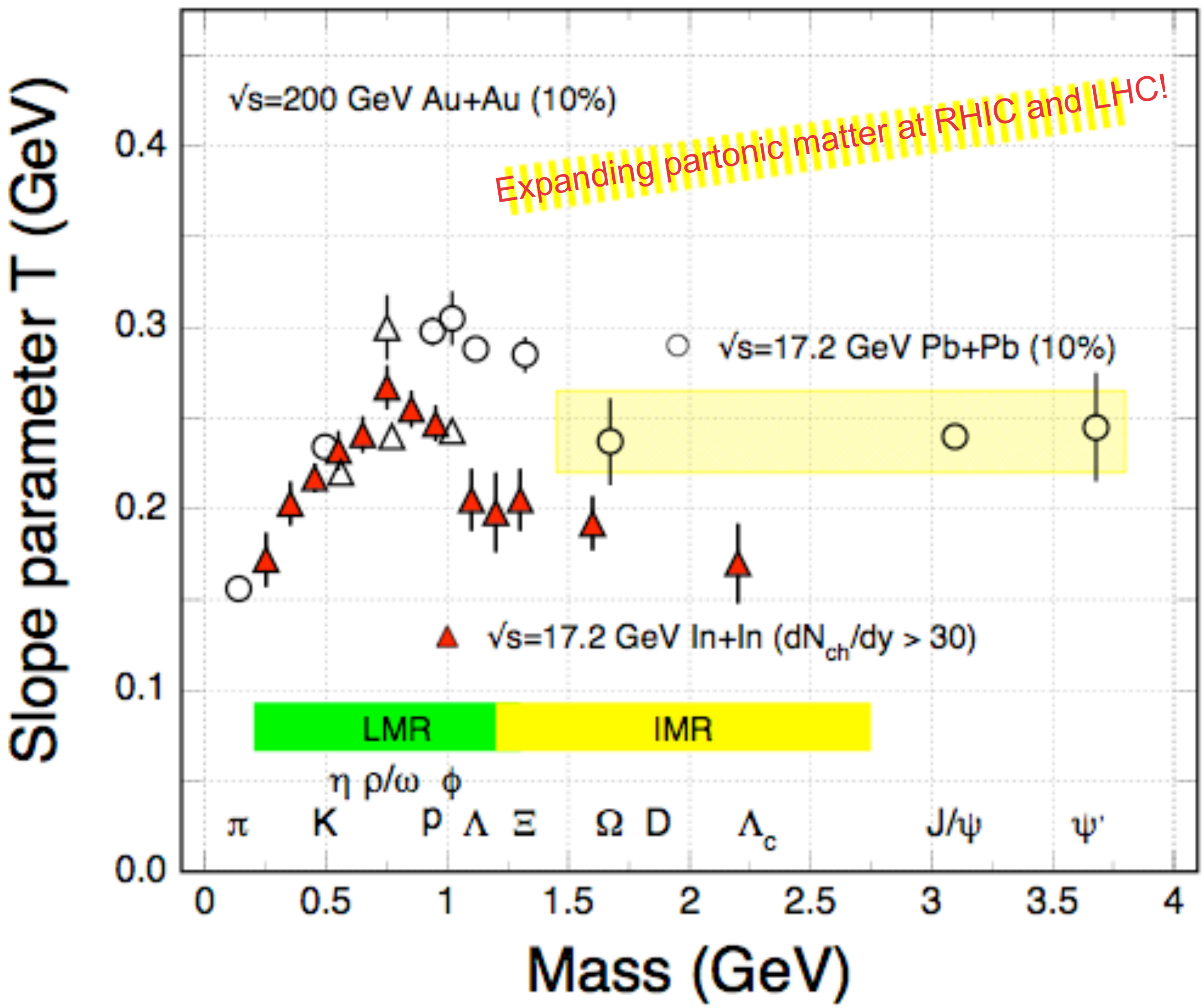
* STAR: 1004.4959, accepted by PRL(2010).
** M. Stephanov: PRL,102, 032301(2009).
*** R.V. Gavai and S. Gupta: 1001.2796.

Di-lepton Program at STAR



Key measurements: ***yields, mass, R_{AA}, v_2*** ➔ *thermalization, thermal rates*

Direct Radiation Measurements



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

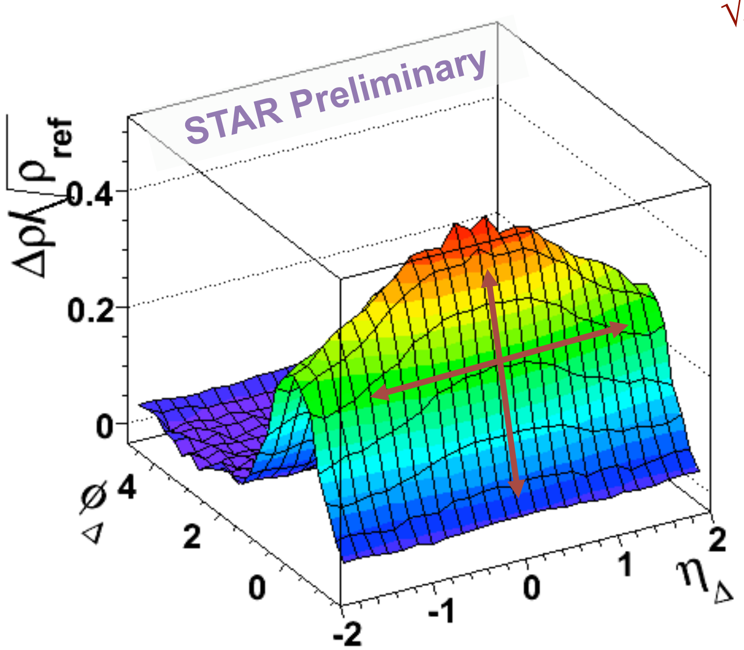
- Low mass region:
  $\rho, \omega, \phi \Rightarrow e^-e^+$
  $m_{inv} \Rightarrow e^-e^+$

  medium effect
  Chiral symmetry

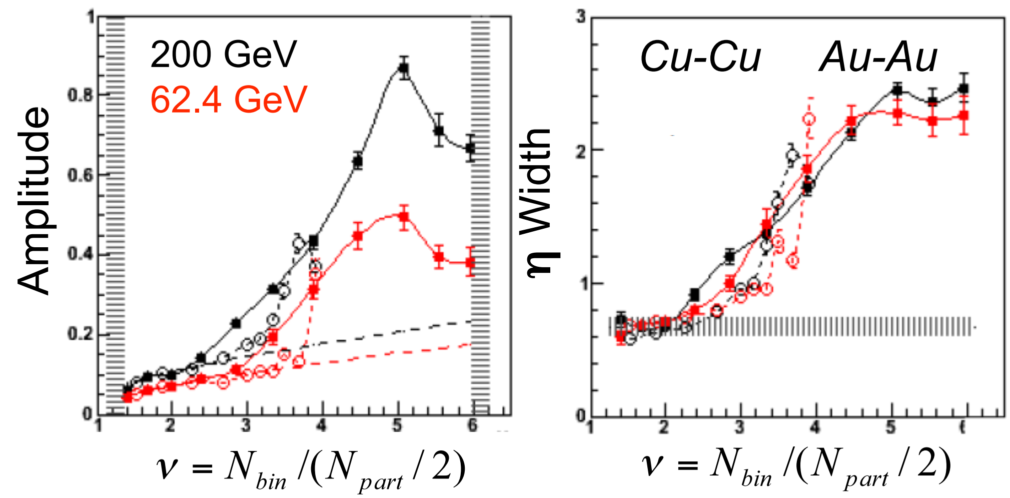
- Intermediate region:
  $J/\psi \Rightarrow e^-e^+$
  $m_{inv} \Rightarrow e^-e^+$

  Direct radiation

Multi-particle Correlations, Ridge



$\sqrt{s_{NN}}$ = *200* GeV Au+Au collisions

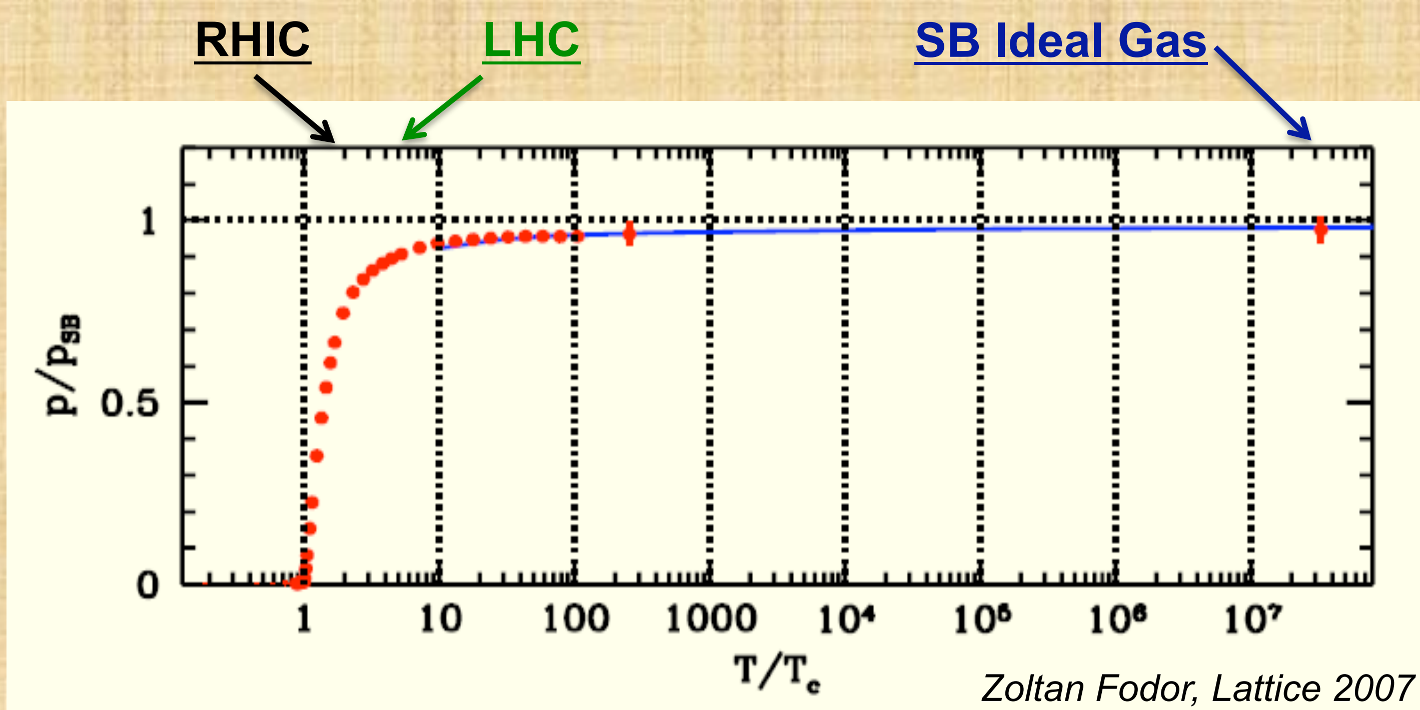


(h±: 30-40% central, p_t > 0.15 GeV/c)

1) Long range correlation (η_Δ) carries essential early collision dynamics
2) Inter play between energetic partons, collective flow, thermalization
   - CGC, Glama, energy loss, …
3) Connection to initial condition and thermalization

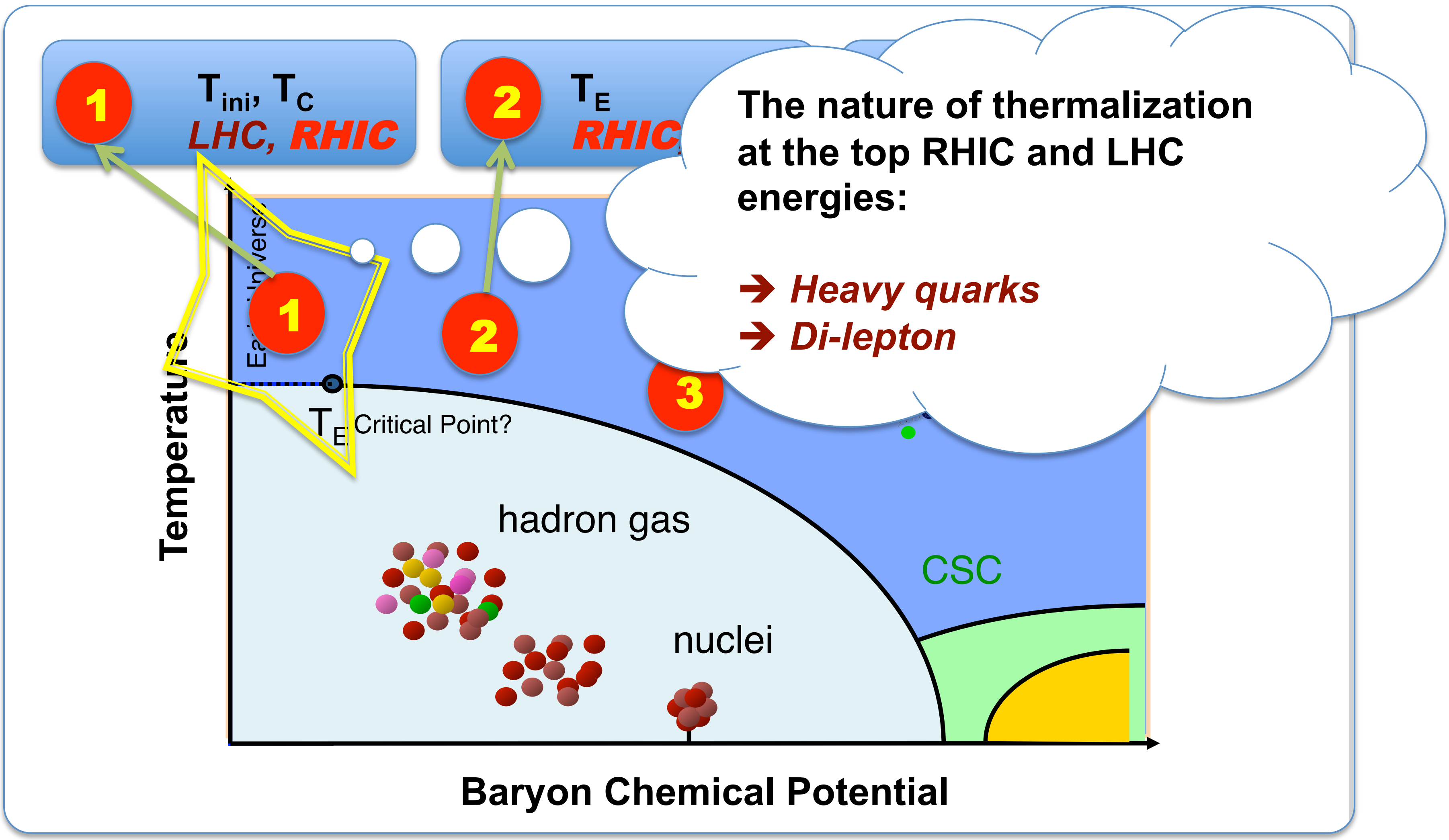
J. Takaharshi *et al*, PRL **103**, 242301(2010)

QCD Thermodynamics



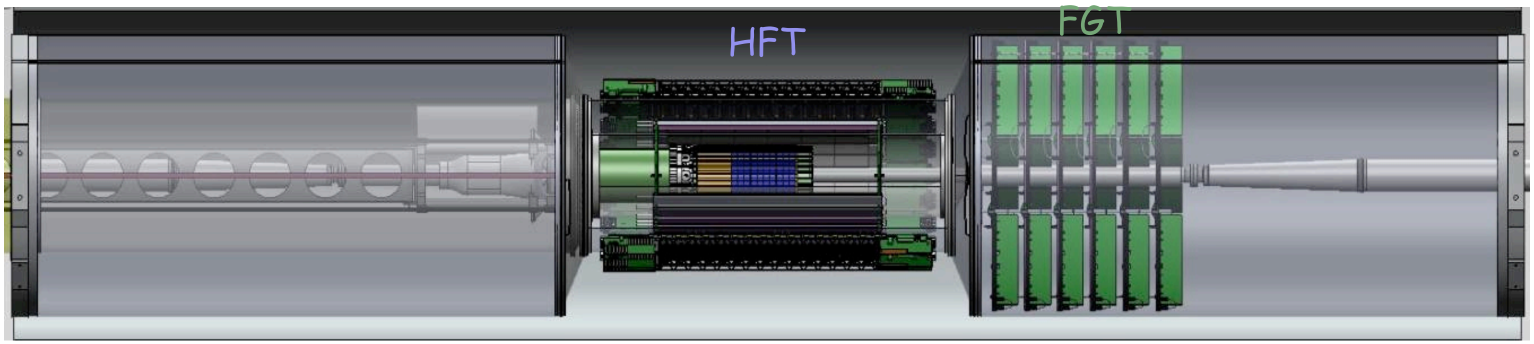
1) At $\mu_B = 0$: cross over transition, $150 < T_c < 200$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)
4) Thermalized, evolutions are similar, RHIC and LHC

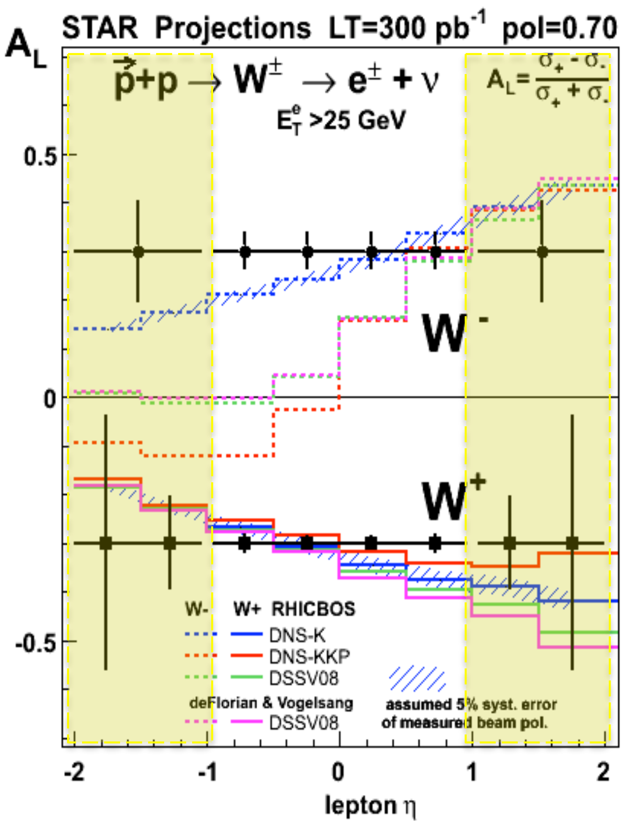
The QCD Phase Diagram and High-Energy Nuclear Collisions



STAR Upgrades

Forward GEM Tracker (FGT)

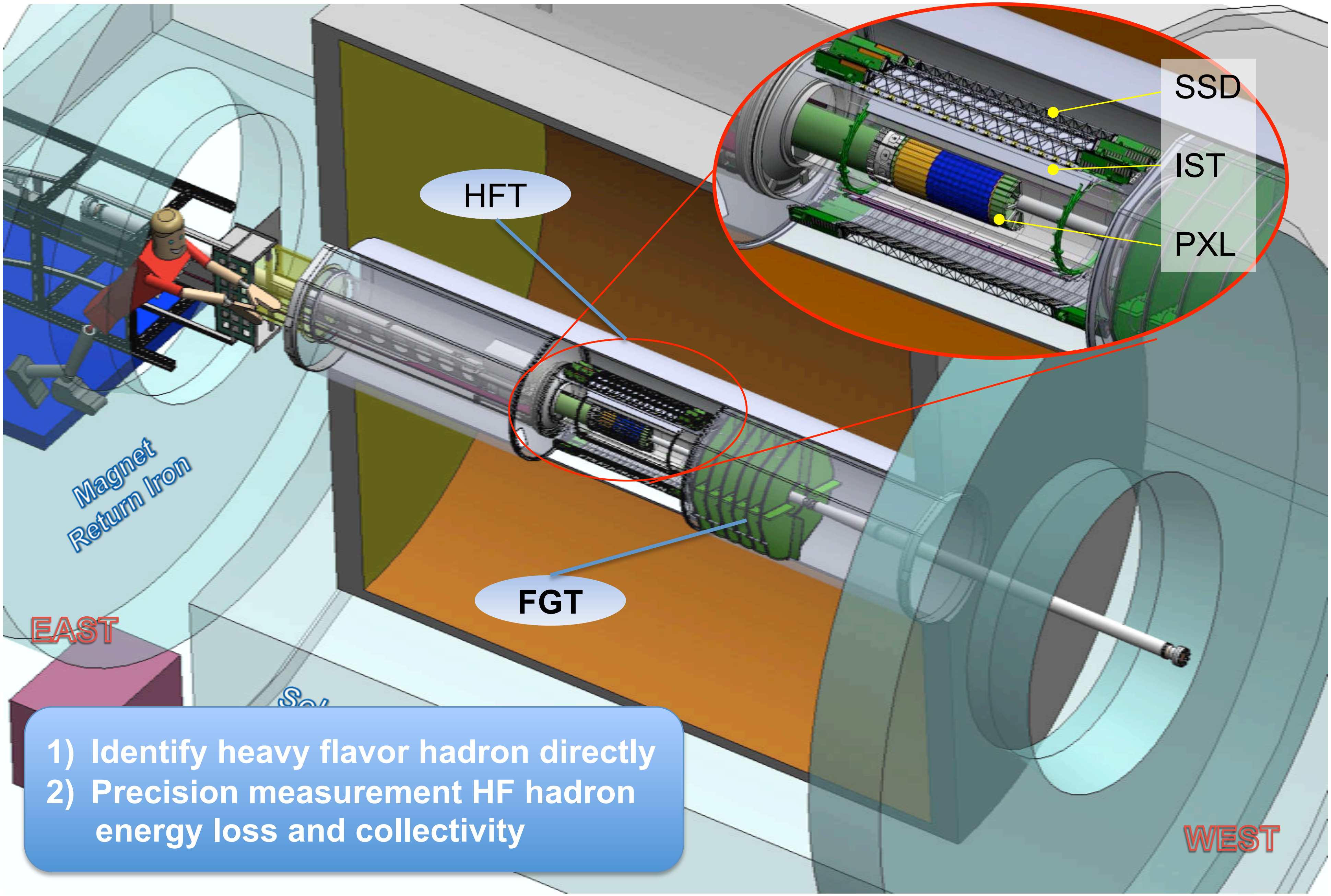




1) Six light-weight triple-GEM disks
2) New mechanical support structure
3) Planned installation: Summer 2011

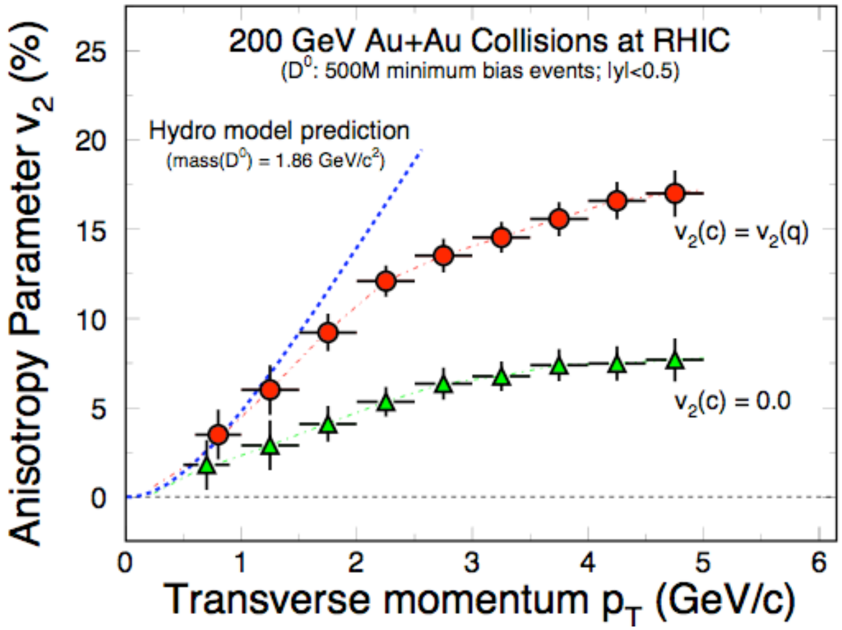
1) Full charge-sign discrimination at high-p_T
2) Design polarization performance of **70% or better** to collect at least 300pb^{-1}
3) **Ready for Run 12!**

Heavy Flavor Tracker (HFT)



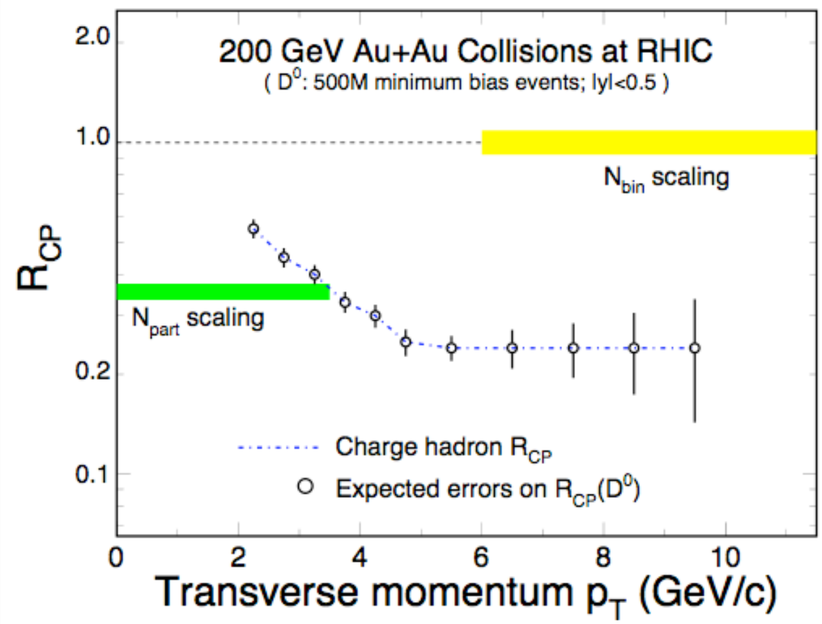
1) Identify heavy flavor hadron directly
2) Precision measurement HF hadron energy loss and collectivity

HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

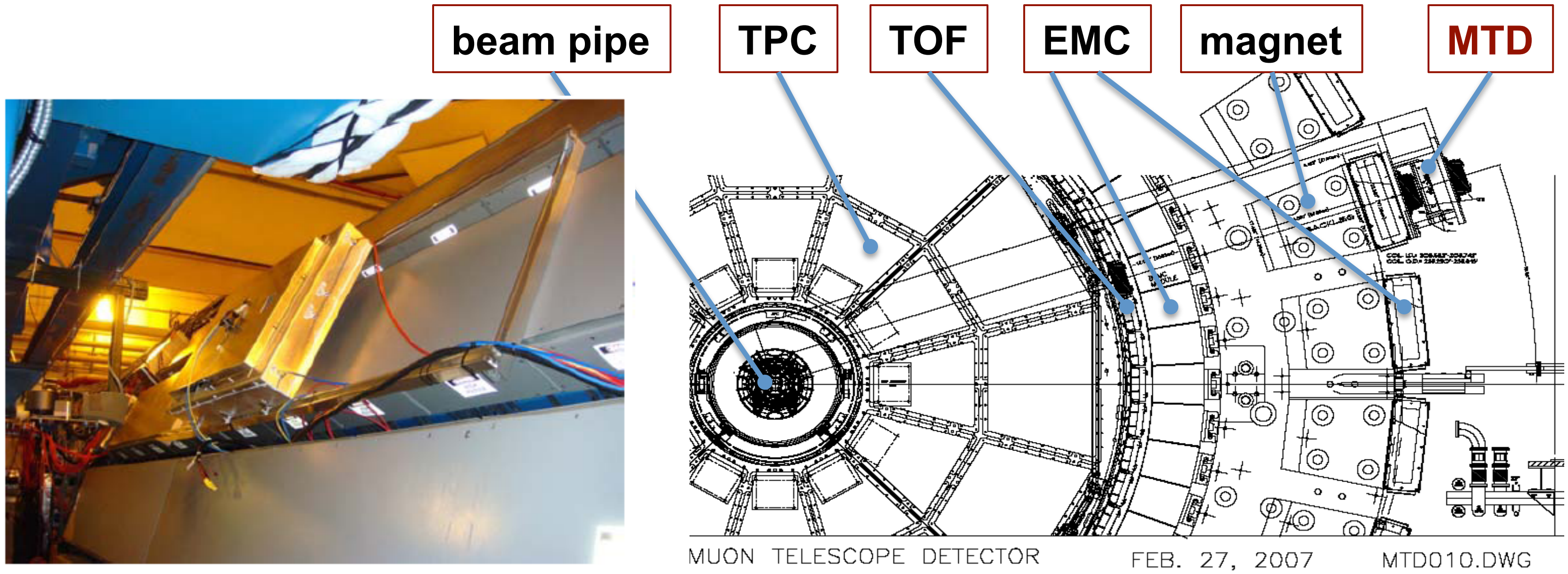
Medium properties!



- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

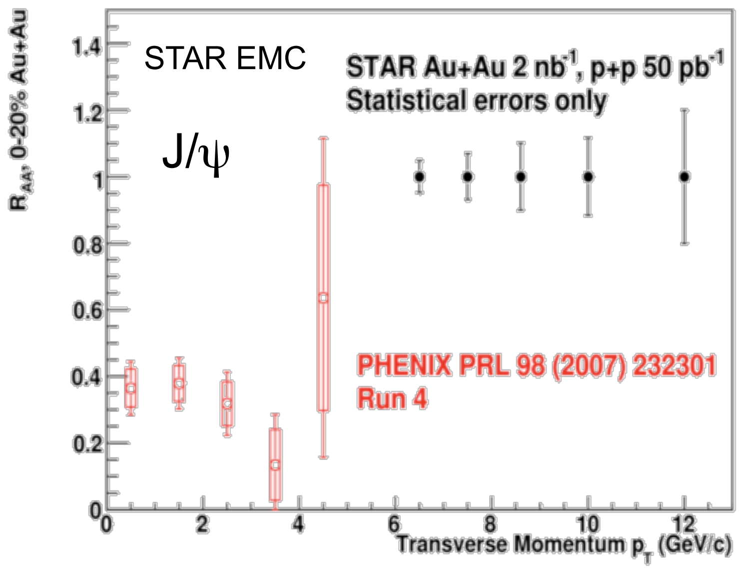
Muon Telescope Detector (MTD)

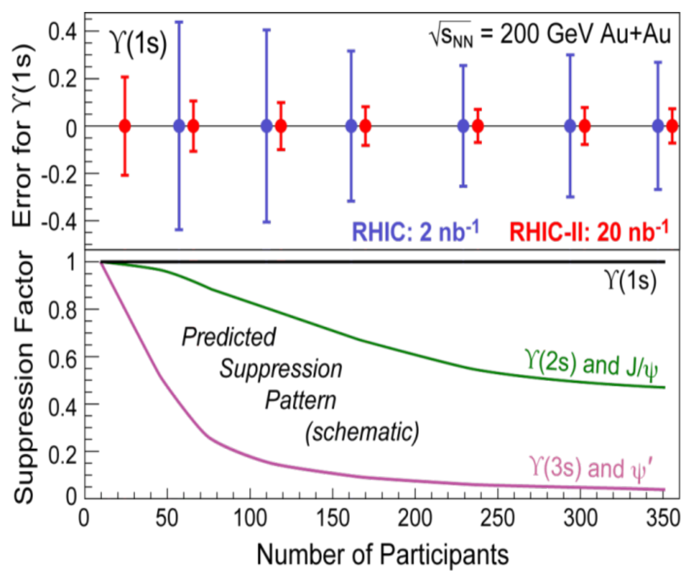


Muon Telescope Detector (MTD) at STAR:

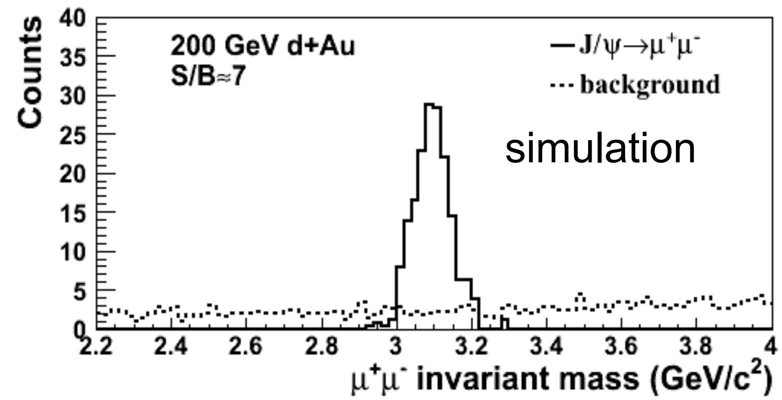
1) MRPC technology; μ_ε ~ 36%; cover ~45% azimuthally and $|y| < 0.5$
2) TPC+TOF+MTD: muon/hadron enhancement factor ~ $10^{2\text{-}3}$
3) For high p_T muon trigger, heavy quarkonia, light vector mesons, $B \rightarrow J/\Psi + X$
4) China-India-STAR collaboration: a proposal sub. to BNL 02/2010.

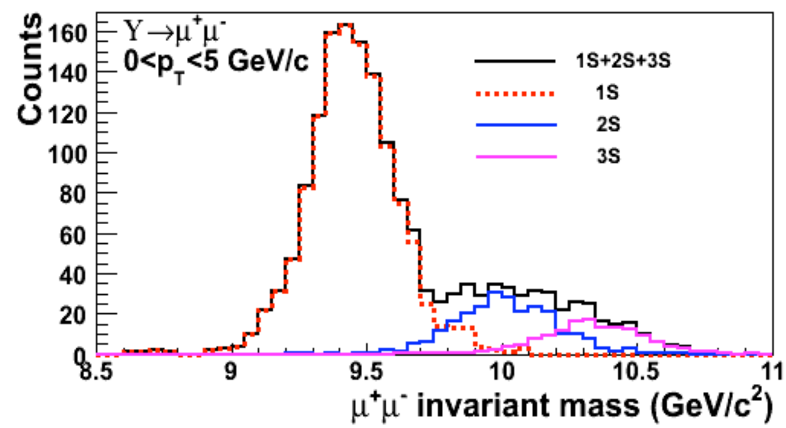
Heavy Quarkonia: J/ψ and ϒ





The Muon Telescope Detector

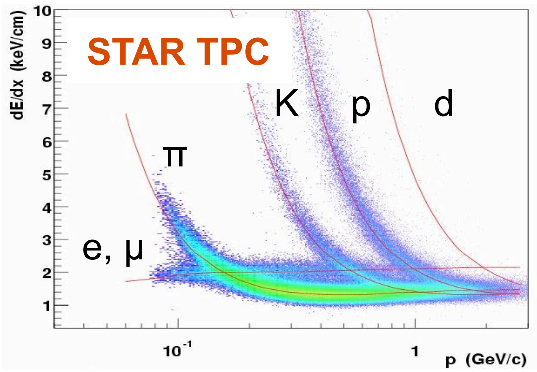


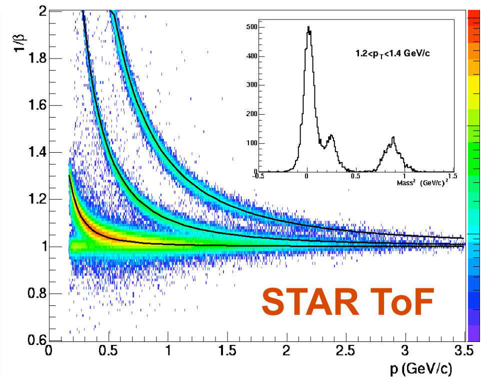


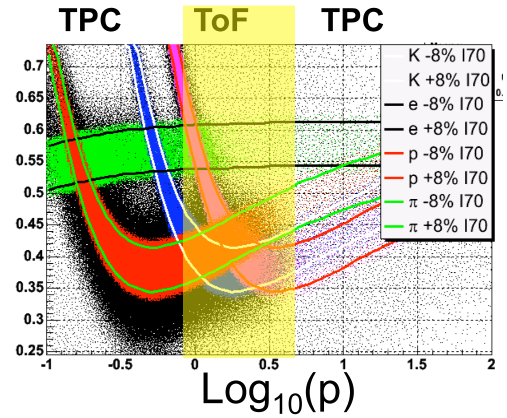
MTD: excellent mass resolution for ϒ

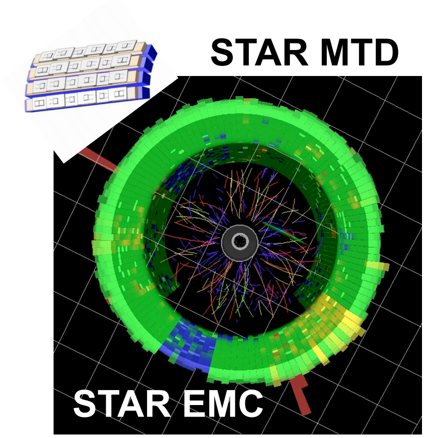
L. Ruan *et al.*, 0904.3774, JPG36(2009)

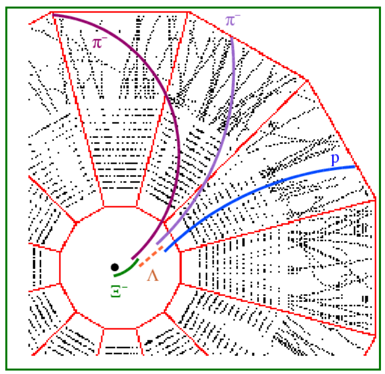
Particle Identification at STAR

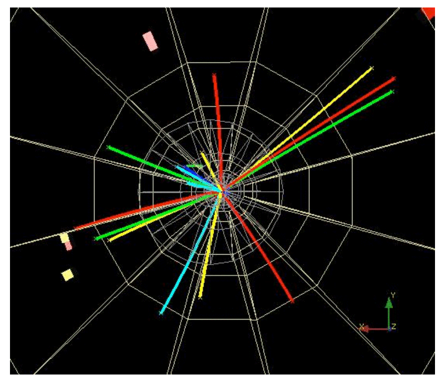


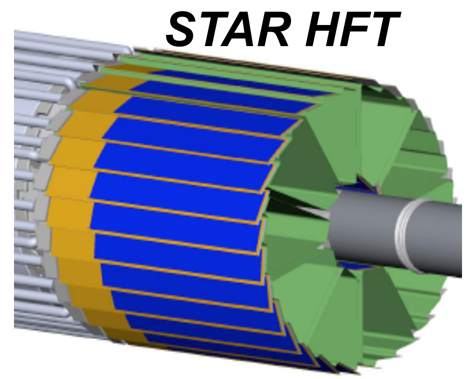












Neutral particles **Strange hyperons** **Jets** **Heavy Quark Hadrons**

Multiple-fold correlations among the identified particles!

Summary

STAR QCD physics program for next decade:

Spin Physics: (cold nucleon)

- 200 GeV: ***Δg*** inclusive and di-jets, γ-jet
- 500 GeV: ***sea quark*** helicity distributions
- 200/500 GeV: transverse spin phenomena

Low-x Physics: (cold nucleus)

- Study gluon-rich phenomena at RHIC
- Color glass condensate

Heavy Ion Physics: (hot nuclear matter)

- Thermalization at 200 GeV
- QCD phase boundary and critical point, started.
- In medium properties